JACOBS

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BY

CHARLES MATTATHIAS JACOBS, M. Inst. C.E.

WITH AN ABSTRACT OF THE DISCUSSION UPON THE PAPER.

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Excerpt Minutes of Proceedings of The Institution of Civil Engineers.

Vol. clxxxi. Session 1909–1910. Part iii.

LONDON:

Published by The Institution,

GREAT GEORGE STREET, WESTMINSTER, S.W.

[Telegrams, "Institution, London." Telephone, "Westminster 77."]

1910.

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LONDON: PRINTED BY WILLIAM CLOWES AND SONS, LIMITED,
DUKE STREET, STAMFORD STREET, S.E., AND GREAT WINDMILL STREET, W.

THE INSTITUTION OF CIVIL ENGINEERS.

SECT. I.—MINUTES OF PROCEEDINGS.

22 February, 1910.

JAMES CHARLES INGLIS, President,
in the Chair.

(*Paper No. 3859.*)

"The Hudson River Tunnels of the Hudson and Manhattan Railroad Company."

By CHARLES MATTATHIAS JACOBS, M. Inst. C.E.

IT is not often that so many years elapse between the inception and the completion of an engineering project as has been the case with the construction of the tunnels under the Hudson (North) River at New York City. This work has been suspended on several occasions and taken up again under new management, with a different method of operation in view; and the existing system is a very considerable development from the project originally planned.

HISTORY.

The Hudson River is tidal as far as Troy, a distance of 150 miles from its mouth. It flows in a submerged valley, and it is estimated by geologists that a subsidence of about 200 feet has occurred since the glacial period; before that time the river was non-tidal, discharging into the ocean at a point many miles seaward of its present mouth. The river and glacial action have cut a deep channel in the rock, which has been gradually filled with material eroded from the area within the watershed, forming a silt stratum which extends from the bed of the river to the underlying rock and varies in thickness from a few feet to 250 feet. The character of this silt varies with the depth; it is very dark in colour, and contains about 30 per cent. of water. A sample obtained from the "up-town" tunnel at about the deepest point had the following characteristics: specific gravity wet, about 1·65; dry, about 2·50; weight per cubic

foot wet, about 103 lbs.; dry, about 156 lbs. In its natural state it is very soft and flows readily through minute apertures, but when the contained moisture is partially excluded by compressed air, it has many of the characteristics of a stiff clay. It has been used in its natural condition with great success to plaster a heading or shield-face, in order to prevent the escape of air when tunnelling in sand and gravel; and it is practically impervious to water, the tunnels through silt showing less seepage than in any other material met with in the river-tunnels in this vicinity.

The Hudson River is about 1 mile in width and 40 to 60 feet in depth. The greatest depth to rock is near the west side where it is 250 to 300 feet below mean tide, although the deepest water-channel is near the east side. From the east shore to a line about 1,500 feet therefrom the rock is 40 to 60 feet below mean tide. On the New Jersey side the rock is a soft mica schist, while on the New York side it is gneiss: the strike is approximately parallel to the river and the dip is nearly vertical.

For many years no means of crossing this river existed south of Albany, 145 miles up-stream, except by ferry-boats, and continuous land transportation between the New England States and the States to the west and south was thus interrupted. In 1889 the Poughkeepsie bridge was built, crossing the river 75 miles from its mouth. The desire for some means of crossing the river at New York City, other than by ferry, had long been felt, and as a bridge in the state of the engineering art at that time seemed out of the question, a tunnel was considered to be the only means of solving the problem.

Before the completion of the tunnel the traffic crossing the river was handled by large steam ferry-boats, most of which were worked by the railway-lines terminating on the west side of the river. To meet the demands of the traffic a very efficient type of ferry-boat has been developed. These boats are built to move in either direction and load and unload from the ends: access to the shore is had by bridges, the shore end being hinged and the other end resting on a floating pontoon. The vessels have steel hulls, overhanging decks, and a double carriageway for vehicles in the middle, with large cabins on the sides. The more modern boats have an upper deck also, with a large cabin, and provision is made for loading and unloading from both decks. The older boats have side paddle-wheels driven by engines of the diagonal or working-beam type, but the more recent ones have screw-propellers, but fore and aft on a rigid shaft extending from end to end of the vessel. The principal dimensions are:

Length over all	206 feet.
„ of hull	200 „
Beam over guards	65 „
„ of hull	46 „
Depth of hull	17 „
Draught	10 „ 10 inches.
Displacement	890 tons.
Power	1,016 I.HP.
Speed, per hour	12 knots.
Capacity :—	
Passengers, seating 500 standing	1,500
Vehicles (about)	18

In 1895 the Author was invited to report upon the practicability of completing the old Hudson River tunnels and to submit an estimate of the cost. The tunnels, which had filled with water to within 4 feet of the top of the shaft in Jersey City, were pumped out in order to make careful investigation of the condition of the structure. The two special difficulties relating to the continuation of the work were: first, 500 feet of cast-iron lining was closely timbered with 12-inch vertical timbers, and tied with three rows of horizontal turn-buckles to about 4-foot centres to preserve the structure from collapse; and secondly, within 136 feet of the point where the work had been suspended, there was a reef of rock which extended for a length of 750 feet on the line of the tunnel and gradually rose to about 16 feet above the incline of the bottom of the tunnel, the presence of this rock being clearly indicated by numerous borings. The Author stated in his report that the weakness in the metal lining could, in his opinion, be remedied by an internal lining of reinforced concrete, and also that the shield could be carried through the reef if an apron were added to the front of it for the protection of the men when drilling the rock, the Author's previous experience in meeting similar difficulties in the construction of the East River tunnel for gas-mains in 1892 having indicated that this was feasible. Although the report was favourably considered, nothing was done until the 6th February, 1902, when a new company was incorporated under the name of the New York and Jersey Railroad Company, and the Author was retained as Chief Engineer. Plans and specifications were drawn up to cover the construction of tunnels extending to a station in Christopher Street, New York City, adjoining the Ninth Avenue elevated railroad station, and leading contractors were invited to tender for the execution of the work. Only one tender was submitted, which was entirely unacceptable; consequently, the whole of the work, including the entire system of tunnel-lines, was carried out by a construction-

force organized and directed by the Author, with the exception of a short length of the land tunnels built by cut-and-cover methods under contract.

When the New York and Jersey Railroad Company took up the completion of the old tunnels, the length of tunnel already constructed was:—

North tunnel from New Jersey shaft	. . . . . .	3,916 feet.
,, ,, ,, New York ,,	. . . .	160 ,,
South ,, ,, New Jersey ,,	. . . .	570 ,,

The former plans contemplated the use of the tunnels by ordinary steam-trains, but this idea was abandoned on the resumption of work, as it was intended to use vehicles propelled by electricity, for passenger-traffic only. The first plan considered was the completion of the north tunnel only, and the use therein of special narrow carriages on two lines of railway. However, a reconsideration of this plan led to the decision that the capacity of such a line would be insufficient, and it was therefore decided to complete both tunnels and place a standard-gauge line in each. It was further decided to extend the New Jersey approach to a connection with the surface, thus enabling the electric tramcars of Jersey City and Hoboken to cross the river to an underground station to be built at Christopher and Greenwich Streets, New York City. No connection with the electric tramways on the New York side was contemplated; the New Jersey lines are equipped with an overhead contact-wire, while the New York City lines have an underground conductor. Authority for this work was granted by certificate to the New York and Jersey Railroad Company by the Board of Rapid Transit Railroad Commissioners on the 10th July, 1902.

Studies as to the number of passengers likely to use this pair of tunnels led to an investigation of the whole question of the traffic crossing the river by ferry-boats and its probable growth, with a view to carrying it in this and additional tubes.

New York City, in its rapid increase in size and population, has followed the lines of least resistance as influenced by the lines of transportation. Politically, New York, with a population of 3,437,202, is divided into five boroughs, the most populous of which is Manhattan, conterminous with the island of the same name, having a population of 1,850,000 (census of 1900). This island has an average width of $1\frac{1}{2}$ mile and a length of 14 miles. Its growth has been from the south end northward, having been successively stimulated by improvements in transportation-facilities; first, by the elevated railways built between 1870 and 1880 and extended at

various times; secondly, by the electrification of the surface tramways in the years 1895 to 1903; thirdly, by the improvement in speed and capacity of the elevated railways, due to the change in motive power from steam to electricity in 1902 and 1903; and, fourthly, by the opening of the Subway in 1904.

While this development in Manhattan was progressing, improvements in transportation-facilities diverted large numbers to the boroughs of Brooklyn and Queens, across the East River. This was brought about by the construction of the Brooklyn bridge, opened in 1883, and over which the Brooklyn elevated railway trains have entered Manhattan since 1898, and the electric tramways later in the same year; and also by the Williamsburgh bridge, opened in 1903. Owing to insufficient transit-facilities the development of the cities and towns on the west bank of the Hudson River, opposite Manhattan, has not been as rapid as in the corresponding territory across the East River; and although these municipalities are not politically part of New York City, they are essentially part of the same community, and are influenced by the same natural forces which have caused a concentration of population around this great port. However, the fact that they are subject to the laws of another State has placed them beyond the jurisdiction of the various commissions which have been constituted by the State of New York to investigate the transit-facilities of the city and to devise means for improvement; and therefore improved facilities for crossing the river had to be brought about by private enterprise, subject to the laws affecting corporations in the two States and the Interstate Commerce Laws of the United States.

The population of the suburban territory on the west side of the Hudson, within a radius of 20 miles, is about 1,000,000, according to the census of 1900. The volume of traffic crossing the river by the existing ferries, based on statistics for 1903, is about 90,000,000 passengers per annum, with an annual increase of about 5 per cent., of whom more than 75 per cent. cross at points $\frac{1}{2}$ mile to 1 mile south of the tunnels of the original project. A study of these facts led to the conclusion that a single pair of tubes would not be sufficient to handle the existing traffic crossing the river, and that if additional tubes were to be built they would better serve the convenience of the public if situated about 1 mile southward of the earlier tunnels. A tunnel was therefore projected to cross the river on the line of Cortlandt Street to a terminus at the west side of Church Street, between Cortlandt Street and Fulton Street, New York City, returning by another tunnel on the line of Fulton Street, with a station in

Jersey City under the terminus of the Pennsylvania Railroad. This pair of tunnels will, for convenience, be designated in this Paper "down-town" tunnels, and the older tunnels, so long under construction, will be called the "up-town" tunnels. A line was also projected on the New Jersey side to run parallel with the river, connecting the uptown and downtown systems.

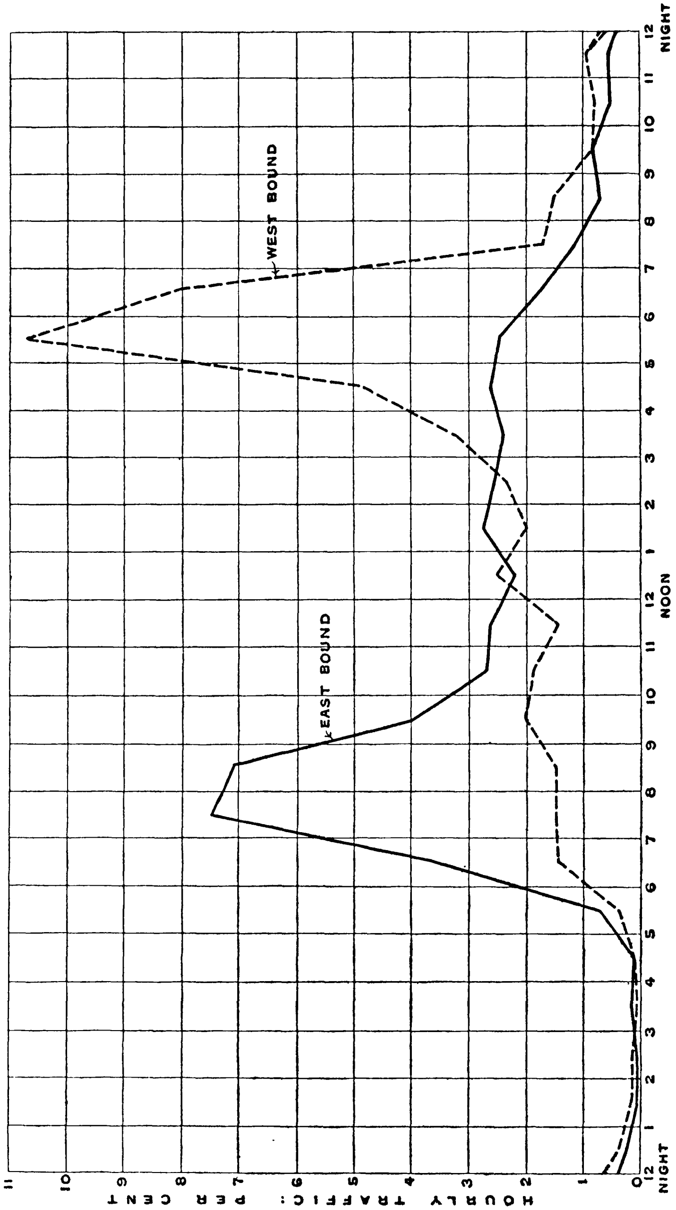
Authority for the construction of the downtown system was granted in the name of the Hudson and Manhattan Railroad Company by certificate of the Board of Rapid Transit Railroad Commissioners on the 24th November, 1903.

A further development of the plan was also adopted, extending the up-town approach inland in New York City to a terminus at Sixth Avenue and Thirty-third Street, with six intermediate stations between the terminus and the river, and with a branch on Ninth Street, extending to Fourth Avenue. This branch would bring passengers to the heart of Manhattan Island (New York City), and also enable them to transfer to two of the elevated railway-lines and to the Interborough Rapid Transit Subway. Authority for this extension was granted by certificate of the Board of Rapid Transit Railroad Commissioners on the 2nd February, 1905.

After the up-town tunnel had been completed and put in service as far as Twenty-third Street Station, the matter of the position of the New York terminus of this line was reconsidered, and, after careful study of the conditions, it was decided that the line should be extended from Thirty-third Street up Sixth Avenue to Forty-second Street, and thence eastward in Forty-second Street to a terminus under Forty-second Street at Park Avenue, which would place the terminus at a point where passengers could readily transfer to the Rapid Transit subway, the Third Avenue elevated railway, the Forty-second Street tunnel under the East River, and also more especially to the trains of the New York Central and Hudson River Railroad Company and of the New York, New Haven and Hartford Railroad Company at their terminal at this point. Permission to extend the line to this point was granted under certificate of the Public Service Commission on the 4th May, 1909. Construction work will soon commence, and is to be completed within 2 years.

Consideration of the annual increase in the passenger-traffic crossing the river and of the maximum capacity of the proposed tunnels led to the conclusion that they would have very little spare capacity for future growth, and therefore a third pair of tunnels to cross the river was projected, to be built at such times as the conditions should warrant. Rather than place this pair of tunnels parallel to either the up-town or down-town system, it was

Fig. 1.


WEST BOUND
EAST BOUND
HOURLY TRAFFIC: PER CENT
12 NIGHT
NOON
12 NIGHT

thought the traffic would best be handled by tunnels running from the Church Street terminus parallel to the down-town tunnels as far as the river's edge, and then crossing obliquely to the Erie Railroad Company's yards, where a connection with the line connecting the up-town and down-town systems, as well as a connection with the surface lines of the Erie Railroad Company, could be made. These tunnels will be referred to in this Paper as the Erie tunnels, and while they do not form part of the lines recently completed, the work is planned so as to admit of their construction at any time without interruption of traffic, the junction enlargements at junctions and points of crossing having been built as part of the present work. The completion of these tubes in the future will admit of an independent train-service between Church Street terminus and Hoboken or the Erie Railroad without passing through the Pennsylvania Railroad station.

As the urban and suburban passenger-traffic in a great city is not uniformly distributed throughout the hours of the day, transportation lines only work to their maximum capacity for two short periods during the day. As this has a marked influence on the transportation problem, the habits of the population of New York in this respect may prove of interest. The percentage of passengers in each hour of the day is given by *Fig. 1* (p. 9), from records of the Cortlandt Street and Desbrosses Street ferries.

The foregoing considerations led to the abandonment of the plan of using single electric-tramcar units through the tunnel, in favour of a service of multiple-unit trains. This equipment, while making higher speed possible, rendered easier gradients and curves desirable. As, however, portions of the tunnel had been constructed before the final plan was adopted, and with regard to which the original scheme was not well located, it was necessary to adopt heavier grades and sharper curves than would otherwise have been the case had the points to be served and the character of the equipment been known from the start.

Fig. 2, Plate 2, indicates the system as finally located, and Figs. 3 and 4 the profiles of the river-tunnels.

On the 6th December, 1906, the corporations organized for the construction of the various portions of the work were consolidated into one corporation called the Hudson and Manhattan Railroad Company

River-Tunnels.

Active constructional work was commenced in February, 1902, the only plant used which was left by Messrs. Pearson and Son being the original shield in the old and uncompleted north tunnel.

A change in the design of the cast-iron lining was made, the ring being made up of eleven segments and key as before. The dimensions were: skin, $1\frac{1}{2}$ inch thick; flanges, 8 inches deep; rings, $20\frac{1}{4}$ inches long; outside diameter, 19 feet $5\frac{1}{4}$ inches; inside diameter, 18 feet $1\frac{1}{4}$ inch; weight per lineal foot, 7,565 lbs. The first ring was erected on the 22nd October, 1902, and by the 29th November, 1902, 136 feet of tunnel had been constructed, when the cutting edge of the shield came in contact with the rock ledge before referred to.

The unusual problem now presented itself of having to blast rock ahead of the cutting edge of the shield, varying from 1 foot to 16 feet above the cutting edge, superposed by a bed of soft silt saturated with water, with a cover varying from 10 to 15 feet above the crown of the shield and a depth of water above the silt rising from 60 to 65 feet.

The heading in front of the shield was enlarged and solidly timbered to form a working-chamber for the purpose of attaching a steel apron just below the axis and extending across the shield, and projecting 5 feet beyond the cutting edge, so that workmen might have sufficient overhead protection in drilling the rock, and also to act as a material safeguard against the inflow of silt. This work of reconstruction occupied 47 days and was carried out under an air-pressure of 42 lbs. The alterations to the shield being completed, on the 1st February, 1903, progress was resumed with the shield partly in rock and partly in silt. The surface of this rock ledge was very irregular, in some places passing below the line of the tunnel and again above. When not in rock, the shield was forced ahead by the jacks without any workmen being in advance of the diaphragm, the material encountered being forced into the tunnel through one or more doors in the diaphragm. If the shield would not advance with a hydraulic pressure of 3,000 lbs. per square inch on the jacks, the pockets of the shield were excavated and rock and other hard material found holding the shield was blasted away; this pressure on the jacks was determined as the safe thrust the shield would withstand without damage.

In view of the probable disturbance of the river-bed which this blasting would involve, scows holding about 600 cubic yards of clay were held in readiness to be dumped over the point of disturbance

in case of a "blow," which precaution proved to be well justified. Nevertheless, two serious blows entailing the flooding of the tunnel did occur, but on dumping two scows over the break, the escape of air through the river-bed was stopped, enabling the water to be blown out. The workmen succeeded in recovering the heading in 11 hours and 23 hours, respectively, from the time that these blows occurred.

The work of blasting the rock proceeded until the last few feet of the reef were reached, where the rock had now reached its highest point, 16 feet above the bottom of the cutting edge, on the east side of the ridge. The silt at this point was in a semi-fluid state and five barges of clay had been deposited to reinforce it. Very great difficulty was encountered here, due to the clay creeping through to the shield-doors, and all efforts by poling and other mining devices to hold the clay back far enough to enable the drillers to work were unavailing. An unusual method was then determined upon; namely, to bake the clay by means of intense heat. Two large tanks were sent into the tunnel, filled with kerosene under pressure; fine blow-pipes were attached to the tanks, and the fire from the blow-pipes impinged on the exposed clay until it became caked sufficiently dry and hard to overcome slipping. The time occupied in the application of the heat extended over a period of 8 hours and during this time water was played continually on the shield to avoid damage due to the high temperatures. This is believed to be the first time that soft material met with in tunnelling under the bed of a river has been solidified by means of fire while working under an air-pressure of 38 lbs. per square inch. Seven days after passing this high point, the rock disappeared and sand was reached. Construction proceeded regularly for a distance of 740 feet, when the bulkhead at the end of the brick-lined tunnel in New York was reached on the 11th March, 1904, thus completing the first tunnel under the Hudson River. Practically 30 years had elapsed since the work was first started.

The time that elapsed from the date work was commenced under the direction of the Author was 505 days, in which 1,625 feet of tunnel were built, or an average of 3·2 feet per day. During this time, in addition to the delay caused by the alterations and repairs to the shield, work was hindered by a strike of the compressed-air workmen, and, in addition to the two blows of air previously described, nine minor blows occurred. The north tunnel was completed by cutting out the internal parts of the shield and constructing, inside the shell, cast-iron tunnel of the standard external diameter of 16 feet 7 inches, which was adopted for the remainder

of the tubes throughout the system. The annular space between the shell and the smaller lining was filled with concrete and cement grout.

The defective iron lining installed in the early stages of the work was rendered efficient by an internal lining of concrete, and a longitudinal and circumferential reinforcement of twisted steel rods. The original tunnel being 3 feet 3 inches larger in internal diameter than the standard tunnel adopted for the remainder of the work, there was sufficient room to admit of this. The inside lining of concrete was continued until the junction with the standard diameter of tunnel was reached.

In addition to the historic north tunnel of the up-town system, three other tunnels have been driven across the river; the south tunnel of the up-town system, and the two tunnels of the down-town system; one of the latter is on the line of Cortlandt Street and the other on the line of Fulton Street. A standard type of cast-iron lining was used (Figs. 5 and 6, Plate 2), consisting of a ring weighing 11,340 lbs. and made up of nine segments and a key. The metal is $1\frac{7}{16}$ inch thick. Each segment has six holes on the circumferential flanges and three holes on the longitudinal flanges. All joints were machined and were provided with a caulking-space $1\frac{1}{4}$ inch deep and $\frac{1}{2}$ inch wide. In sand or rock each segment was provided with a grout-hole, and in silt one segment only of each ring. All cast-iron lining-plates were, while hot, immersed in a bath of coal-tar pitch.

Where the tunnel was liable to be subjected to undue stresses, the lining was strengthened by reducing the width of the rings to 18 inches, the other dimensions remaining unaltered. The weight of an 18-inch ring was 9,522 lbs. The tunnels were also strengthened at points where extraordinary exterior loads were anticipated, by placing between the cast-iron lining-rings packing-rings consisting of two steel plates $\frac{5}{8}$ inch thick, the ring being made up of four segments, and the joints being so spaced as to break joint with those on the cast-iron lining. In addition to the cast-iron lining, short lengths of tunnel were built with cast-steel lining where there were liable to be concentrated loads due to piles supporting the sea-wall along the edge of the river. The dimensions were the same as for cast-iron lining, except that the bolt-holes were larger to permit of the use of thicker bolts.

The standard bolts were of steel with a rolled thread $1\frac{1}{4}$ inch in diameter at the bottom of the thread. The bolts for the steel rings were $\frac{3}{8}$ inch larger.

SHIELDS.

The shields used in driving the tube tunnels were all built to one design, with some slight exceptions. The outside diameter was 17 feet, the length 11 feet 5 inches. The diaphragm was placed 5 feet 8 inches in rear of the cutting edge. The space in front of the diaphragm was divided into six pockets by one transverse girder and two vertical girders.

The shields were advanced by sixteen 8-inch hydraulic jacks. Water at a pressure of 5,000 lbs. per square inch was taken to the shield from hydraulic pumps placed in the engine-rooms outside the tunnels. The weight of a shield complete with hydraulic machinery, etc., was 61 tons.

Above the transverse girder were three sliding platforms actuated by hydraulic jacks, so that they could be advanced ahead of the cutting edge to provide cover for the men when drilling rock. A removable projecting hood was also provided on the upper cutting edge, extending downwards one-third of the circumference and outwards 2 feet 6 inches, so as to provide head cover for the drills when the surface of the rock was at a higher level than the sliding platforms, and to serve as a poling-board in soft ground.

The first shields were built with the segment-erector attached, but afterwards the erectors were made independent of the shield and carried on a platform moving on rollers connected by brackets with the iron lining. Table I in the Appendix gives the records of the various shields.

SOUTH TUNNEL (UP-TOWN SYSTEM).

Work was commenced on the twin to the old north tunnel—i.e., the south tunnel of the up-town system—by building a shield-chamber at the end of the short section of brick tunnel built by the original company, and 500 feet from the shaft. On the 23rd January, 1903, work was commenced on the installation of the air-locks. The erection here of one of the typical shields started on the 17th July, and was completed on the 24th August, and the first ring of iron was put in on the 22nd September, 1903.

The experience in the north tunnel having demonstrated the fact that the shield could be advanced by the admission of a small quantity of silt through a single door, the standard shields for the remainder of the work were designed with a view to withstand the full power of the sixteen 8-inch jacks, under a hydraulic pressure

of 5,000 lbs. per square inch. It was found that this shield could be easily advanced with the admission of no silt whatever. It was also found, when advancing the shield in the Hudson River silt without excavating, that the shield commenced to move with 1,600 lbs. per square inch on eleven jacks, which was equivalent to a pressure of 3,900 lbs. per square foot on the area of the face of the shield, neglecting friction and assuming that the air-pressure inside the tunnel balanced the hydrostatic pressure outside. At a pressure of 2,500 lbs. per square inch on eleven jacks, equivalent to 6,000 lbs. per square foot on face of the shield, it could advance at the rate of ½ inch per minute.

As the hydraulic machinery was capable of exerting a pressure of 5,000 lbs. per square inch, which, if applied to the sixteen jacks, would be equivalent to a pressure of 17,700 lbs. per square foot on the face of the shield, there was abundant power available for advancing the shield in this way. Usually, three or four of the jacks in the upper part of the shield were not utilized. Whilst the fact that the shield could be advanced without excavation was demonstrated, it was found that better control could be had over the direction in which the shield would move by admitting through the shield-door about 5 per cent. of the material displaced, and this was the practice usually followed.

By thus obviating the necessity of disposing of excavated material, very rapid progress was made; as an instance, in the south tunnel 31 rings, or 62 feet of tunnel, were driven in 24 hours, and 346 feet of tunnel were built in 1 week.

When the shield had advanced 115 feet, being closely alongside the coal-wharf of the Delaware, Lackawanna and Western Railroad Company, with the doors kept closed as previously described, the night superintendent, finding the shield was moving very slowly, determined, contrary to orders, to open one of the upper doors, so as to allow the material displaced by the shield to come in through the door. Work then proceeded for about ½ hour with the shield slowly advancing, when suddenly a column of silt, equal to the cross section of the opening, shot forward and buried one of the men in its rush, the remaining men in the heading escaping by means of the emergency-lock. This section of tunnel became solidly filled with silt in a very short time, and consequently the heading was lost. A method of regaining the heading had to be decided upon at once, and a plan involving the dredging the bed of the river in advance of the shield to sufficient depth to enable a diver to go down and timber up the exterior opening of the doorway, was considered. However, as access to the waters overlying the tunnel was

prevented by their being almost entirely occupied by shipping, and as at that time the railway-company owning the waterway above was not particularly favourable to the enterprise, and would not have granted permission to dredge alongside the coal-wharf, it was abandoned. This difficult situation was met by obtaining two heavy mainsails and making a double canvas cover, about 60 feet by 40 feet. The canvas was then spread on a flat barge, small sections of pig iron being secured round the edges of it; lines were carried to fixed points to hold it in the exact position; and, when the barge was withdrawn, the canvas was allowed to drop to the bed of the river, so that 30 feet overlapped the shield, and the remaining 30 feet lay out beyond the face, a large number of bags of silt being then deposited on the canvas. One of the pipe-valves in the air bulkhead which separated the flooded portion of the tunnel from the remainder was then opened and the silt, under the direct hydrostatic pressure of the river, shot into the tunnel westward of the bulkhead a distance of 40 feet, and cars were filled with it for 8 days continuously. The removal of the material formed a cavity in the bed of the river outside the cutting edge of the shield until the canvas dropped and was eventually drawn into the opening of the doorway through which the silt was passing, finally blocking it. Additional material was then deposited from the river-surface to fill the cavity and hold the canvas in place. The lower lock-door was then forced forward by means of jacks, and a chamber was formed large enough for the admission of air-pressure. Workmen were then sent into the tunnel to excavate the material; this occupied 9 days until the heading was reached and the door on the inside of the shield was closed.

Progress was resumed on the 23rd November and continued until the 1st April, 1904, when work was suspended pending approval by the city authorities of the plans for extending the New York approach to Thirty-third Street and Sixth Avenue, New York City, and in order to obtain a right of way for the New Jersey approach across the property of the Delaware, Lackawanna and Western Railroad Company. The practicability of driving a tunnel across the river having already been demonstrated by the completion of the north tunnel, it was considered useless to make the large expenditures for the south tunnel until the work could be pushed simultaneously on the approaches.

On these matters being satisfactorily adjusted, work was resumed on the 24th August, 1904. The lower part of the shield encountered rock on the 26th February, 1905, and work continued with the surface of the rock alternately rising above and dropping below the bottom of the tunnel until the 8th June, when rock was finally

passed. From the time the shield first struck rock to the time it left was 103 days; the total distance was 668 feet. After leaving rock, work was continued in silt and sand until the 25th August, 1905, when the bulkhead at Morton Street shaft, New York City, was holed through. The total time since the work was started, deducting the time when work was suspended, was 562 days, the length of tunnel built being 5,206 feet, or an average of 9·3 feet per day. No blows of air serious enough to stop work occurred.

All shields rotate more or less in soft ground, and the south-tunnel shield, just before reaching the rock ledge, had rotated 17°, thus placing the advanced tables, or aprons, so much out of the horizontal plane that their effectiveness was impaired. The openings of the shield were, of course, at a similar angle. The method used to bring the shield to its normal position consisted of equipping every alternate jack with the arrangement of steel wedges indicated in Fig. 7, Plate 2; one set of wedges was attached to the rams, and the opposing set was attached to the lining-plates by bolts passing through the bolt-holes. When the pressure was applied to the rams, the inclined faces of the wedges created a tendency for the lining and the shield to rotate in opposite directions; and as the rings could not move, the rotary motion was confined to the shield and continued at each advance until the horizontal position was attained.

Down-town Tunnels.

Work on the down-town system of tunnels was started in March, 1905, by the construction of a shaft, called the "Pier C shaft," on the New Jersey side. Owing to the fact that these tunnels were to be started immediately under the Jersey City terminus of the Pennsylvania Railroad Company, it was impracticable to sink a construction-shaft near the line of the tunnels; it was therefore necessary to locate it 387 feet southward of the nearest tunnel, and to build a heading from the shaft to the tunnels. This shaft was conveniently situated so that materials could be transported to and from it by water, and was constructed of tunnel-rings 19 feet 5 inches in diameter.

The lower part of the shaft was not lined, and when it had reached a depth of 81 feet, a heading 15 feet wide and 10 feet high was tunnelled in the rock to the line of the tunnels. Both tunnels were then driven towards the river for a distance of about 100 feet, where chambers were excavated for the erection of the shields. Test borings indicated that the surface of the rock dropped

sharply as the river was approached, and these shield-chambers were built, with a roof arching of iron segments supported by concrete side walls, as near the river as was considered safe. Bulkheads with air-locks were installed close to and landwards of the shield-chambers.

Fulton Street Tunnel, Westbound (Down-town System).—The first ring in the westbound tunnel was erected on the New Jersey side on the 6th February, 1906, and as the shield advanced, the surface of rock rapidly declined, falling below the top of the shield shortly after leaving the shield-chamber. Progress was slow with the upper part of the shield in river-silt and the lower part in rock until the 14th April, when the latter was cleared and work then advanced rapidly in the river-silt until the 18th September, when rock was again encountered. The average progress while in the silt was 12·4 feet per day; the maximum progress in 24 hours, on the 26th July, 1906, was 66 feet; and in 1 week—from 8.0 a.m. on the 23rd July to 8.0 a.m. on the 30th July, 1906—an advance of 290 feet was made. The surface of the ledge of rock in the river on the line of the Fulton Street and Cortlandt Street tunnels was much higher than the corresponding ledge on the line of the up-town tunnels; so much so, that for a long distance the tunnels were excavated entirely in rock. The shield, partly in rock and partly in silt, continued for a distance of 361·4 feet until the 14th March, 1907, and was thereafter continued wholly in rock until the 3rd September, 1907, when it was stopped to enable the portion of the eastbound tunnel connection with the Erie Railroad to be built where it crosses under this tunnel. This portion of the under tunnel was built by removing the bottom segments of the iron lining after the shield had passed, excavating the rock, and afterwards lining it with concrete. Work in the upper tunnel was resumed on the 10th December, 1908, and continued with a bottom heading until the meeting with the heading driven from New York.

As the rock section to be traversed was 2,300 feet long, progress was slow. It was concluded that, in order to expedite the work, shields should be started from the New York side to meet those in the rock reef referred to. A compressor-plant was therefore installed and shields were erected in the ends of the concrete approaches to the Church Street terminal. The first ring of the Fulton Street tunnel was erected on the 11th September, 1907, and the shield was driven beneath a narrow street in sand with great care to avoid damage to adjoining buildings, until the 27th November, 1907, when work here was suspended, 589 feet of tunnel having been completed. Work was resumed on the 24th August, 1908, and rock was met

with on the 19th September, a full face of rock being encountered on the 15th November, 1908. A bottom heading was thereafter continued until the 20th November, 1908, when a fissure was encountered, causing a bad blow which flooded the tunnel. This blow caused some delay, as no large quantity of clay could be dumped over the line of the tunnel as usual, owing to the fact that the river over the tunnel was almost continuously occupied by a transatlantic steamship line. The blow was finally stopped and work resumed on the 2nd December, the advanced headings met on the 11th March, 1909, and the shields which followed met on the 20th May.

Cortlandt Street Tunnel (*Eastbound*).—The conditions met in constructing the eastbound tunnel were very similar to those in the westbound, and the two were constructed simultaneously. The shield started from the shield-chamber in the rock on the Jersey City side on the 26th January, 1906, and entered the full silt on the 19th April after traversing 177 feet. Rapid progress was made in the silt for a distance of 2,813 feet, the average advance being 18·9 feet per day; the maximum for 24 hours was 72 feet, on the 14th August, 1906; the maximum for 1 week (8.0 a.m. on the 8th August to 8.0 a.m. on the 15th August, 1906) was 154 rings, or 308 feet; and rock was again encountered on the 14th September. In November, 1907, work was suspended here until November, 1908, when it was resumed, the shields meeting on the 9th March, 1909.

In order to avoid damage to street structures, great care had to be exercised in driving the tunnel in Cortlandt Street, as the side of the shield was for some distance within a few inches horizontally of the building-front in the street above. The material driven through was a fine sand with very little stability, and, in order to prevent it from running, cement grout in the rear of the shield was used very freely.

In addition to the short lengths of tunnels for future connections with the Erie Railroad, which were built where that line crossed under the westbound river-tube, short lengths of these tubes were built on Cortlandt Street and Fulton Street, where shields were driven out of the Church Street terminal—94 feet on Fulton Street and 90 feet on Cortlandt Street.

NEW YORK APPROACHES (UP-TOWN TUNNELS).

While the construction of the tunnels beneath the river was difficult and dangerous, the construction of the approaches on the land also involved some unwonted problems.

This work was started by building a shield in the old Morton Street shaft and driving inland, the westbound tube being driven first. Considerable difficulty was experienced in driving the shield through the side of the old shaft, as the surrounding material had been very much disturbed when the shaft was sunk. The stratum encountered was a running sand and required very different treatment from that employed in the river-silt. It was necessary to board the face tightly to prevent the sand from running. While the shield was advancing the breast-boards were supported by timber struts extending through the doors to beams placed across the tunnel. The shield advanced up Morton Street to near the corner of Greenwich Street, when it was stopped pending authority to extend the New York approach to Sixth Avenue and Thirty-third Street. The original plans contemplated the construction of the tunnel in concrete, by cut-and-cover methods, from the intersection of Morton and Greenwich Streets to a terminus at Christopher Street, the rails in the proposed terminus to be about 18 feet below the street. The permission for extension of the tunnel to Sixth Avenue required it to be built at a sufficient depth to permit of future subways to cross over between it and the surface of the street, which placed the top of the tunnel at a minimum of 20 feet below the surface. This increase in depth led to the shield method of construction being extended to Sixth Avenue.

On resumption of work it was decided to drive the shield sharply round from Morton Street into Greenwich Street, and this, with the narrow right of way obtained, made it impossible to use a longer radius than 150 feet for the curve; while from Greenwich Street into Christopher Street a curve of 168·5 feet radius was used. The driving of the shields on these curves was a delicate operation, not only on account of the difficulty of making the shield follow the curve truly, but also because of the inevitable void on the outer side of the curve between the iron and this unstable ground, due to the necessarily considerable clearance between the tail of the shield and the iron. There were besides heavy buildings immediately over the tunnel, the basement of the building on Morton Street being 22 feet above the crown of the tunnel, and that of the Christopher Street building 15 feet. On these curves a special iron lining was used, the outside diameter being reduced by 1 inch to 16 feet 6 inches and the depth of the flanges from 8 to 7 inches, thus allowing more clearance between the lining and the tail of the shield and enabling the latter, without binding on the iron lining, to round the curve more readily.

The curve of 150 feet radius mentioned above was driven success-

fully without causing any noticeable settlement of the overlying property; in fact, the tenants of these houses were not aware of the proximity of the tunnel until after the shield had passed their buildings. Very careful work was required under Greenwich Street, with the columns of the elevated railroad overhead: here the two tubes are 18 feet between centres, and the space between them is 17 inches. The elevated railroad at this point is built with independent tracks, the columns of each track not being connected laterally. The combined dead and live load on each of these columns, spaced 39 to 56 feet apart, was about 75 tons. The shields were driven under or adjacent to these columns without causing any perceptible settlement; the only precaution taken was to connect opposite columns together with temporary girders.

The tunnels were driven up Christopher Street without unusual difficulty, except that rock with sand formation above was encountered for a distance of 2,000 feet, the rock reaching a maximum elevation of 16 feet above the bottom of the tunnel.

At Christopher Street and Sixth Avenue the shield of the westbound tunnel was turned into Sixth Avenue by a curve of 150 feet radius and driven up Sixth Avenue to Twelfth Street, where cut-and-cover work commenced. The shield of the eastbound tunnel in Sixth Avenue was turned into Ninth Street, and here a shield-chamber was excavated and timbered, in which a new shield was erected and driven up the Avenue (Figs. 11, Plate 3).

Again great care had to be used in driving the shields under Sixth Avenue, to avoid damaging the structures above, consisting of a large sewer, a double-track tramway on the surface, and a double-track elevated railroad, as well as numerous gas-, water- and other pipes. In order to avoid any sudden settlement of the elevated-railroad structure, due to a possible flow of material into the face of the shield, each column was temporarily supported by a pair of steel girders, one being placed on each side of the column; brackets were riveted to each column and wedges were driven between the girders and the brackets, the former resting on wooden blocks placed on the street-surface. The material encountered was rock with sand above, as far as Eleventh Street, north of which it was sand.

Cut-and-Cover Work in Sixth Avenue.—Owing to the ascending gradient of the tunnels northwards in Sixth Avenue bringing them nearer to the surface, the tunnels were built by cut-and-cover methods north of Twelfth Street, and after consideration of various plans, a twin-tunnel design in reinforced concrete was adopted. The system throughout consists of separate tubes, or tunnels, for each

track, except at crossover switches and at three stations. This isolation of each railway track in the tube tunnels is continued wherever possible, and is obtained in the twin-tunnel section by means of a central concrete wall. This separation of tracks, by maintaining currents of air in the direction of traffic, simplifies the ventilation.

Sixth Avenue is a very congested thoroughfare in the shopping-district, and one of the conditions attached to the permission granted by the municipal authorities to build the tunnel, was that this street should not be closed to traffic while the work was progressing. In addition to the ordinary traffic on the surface, the electric tramway, the elevated railway, and numerous water- and gas-pipes, electric conduits, etc., had to be maintained in uninterrupted service. The problem, therefore, was to construct a railway beneath an existing railway on the surface, with an elevated railway superimposed, in a busy city street, without suspending the traffic on either the railways or the street.

As this subway, so near the surface of the street, conflicted with the main sewer on Sixth Avenue as well as with the sewers on the cross streets, it necessitated the construction of a new trunk sewer under Eighteenth Street from the Hudson River to Sixth Avenue, at such a gradient that it passed under the subway, and also sewers on each side of the subway to provide drainage for the houses, and to receive the flow from the intercepted sewers of the cross streets.

The stages in the method of supporting the various structures while the work progressed were the following:—First, excavation of a pit on each side of each column down to the level of the bottom of the subway, in which pits portions of the permanent concrete floor were constructed; secondly, erection in these pits of wooden trestles extending to above the surface of the ground, to support steel girders which in turn supported the columns, the load being picked up by driving wedges between the top of the girder and brackets riveted to the columns; thirdly, excavation and construction of the full section of the subway under a pair of columns; fourthly, the construction of the permanent foundation for the columns up from the roof of the subway, the removal of girders and trestles, and the completion of the section of subway between the columns.

New Jersey Approaches.

The up-town tunnels on the New Jersey side are so arranged as to enable trains from the up-town systems to run to Hoboken, the Pennsylvania Railroad, or to Summit Avenue, Jersey City, and to

accomplish this complicated the arrangement of the junctions of the various lines. At the intersection of the up-town river-tunnels with the line parallel with the river, extending from the Pennsylvania Railroad station to Hoboken, a triangular, or **Y**, junction was formed, so as to enable trains crossing the river from New York to proceed northward to Hoboken or southward to Jersey City, or vice versa. If this junction had been constructed with the tracks on the same plane, dangerous crossings would have existed, and in order to avoid this the tunnels for trains moving in opposite directions were placed one above the other, instead of side by side as usual. This arrangement not only avoided dangerous crossings but also simplified the construction of the necessary enlargements for switches, these enlargements being constructed of reinforced concrete sunk as caissons from the surface, as hereafter described under a separate heading (Figs. 9, Plate 2). As there was not sufficient distance between the ends of the old tunnels at the Fifteenth Street shaft and the first switch enlargement, in which to separate the tunnels so that one could be carried above the other without the use of excessive gradients, it became necessary to rebuild the first 500 feet of the old south tunnel adjoining the shaft. This was accomplished by erecting a shield in the same shield-chamber that was built for the south-tunnel river-shield at the end of the old brick tunnel, and driving westward towards the shore, using a slightly descending gradient; as the old tunnel was on a very sharp ascending gradient, they quickly separated, the shield cutting through the bottom and sides of the old brick tunnel until the outside of the iron lining entirely cleared the invert of the old brick lining, and passed on under the bottom of the shaft. In order to accomplish this it was necessary to place a bulkhead and air-locks in the old tunnel and to have access to the shield from the New York shaft; but as soon as the shield had been driven to a point where the deviation brought the top of the new tunnel slightly above the bottom of the old, several top segments were removed from the iron tunnel, a lift was installed and material was taken out of the tunnel through the Fifteenth Street shaft. The connection between the switch enlargement caisson and the north tunnel was driven westward by installing a shield in the short section of double-track tunnel east of the shaft, and as it was necessary to cut a passage for the shield through the wall of the shaft, compressed air was installed in the shaft to ensure its being done with safety. An air floor, consisting of an inverted dome of concrete, was built in the shaft above the level of the tunnel, and as the upward pressure of the air acting on this floor was greater than its weight, together with the weight of

the walls of the shaft, the floor was loaded with pig-iron and the space above was filled with water to prevent it from lifting. While this tunnel was progressing, access to the shield was obtained from the New York shaft, communication through the Fifteenth Street shaft being temporarily cut off; but as soon as the tunnel had been driven a short distance beyond the shaft, a standard bulkhead with air-locks was installed and the pressure was removed from the shaft, the air floor was cut out, and access to the workings by this shaft was resumed.

In driving these tunnels westward from the shaft the deeper one was kept slightly in advance of the other until both arrived at the switch enlargement known as "caisson No. 1," which had previously been constructed. The concrete tunnel-plugs in this caisson were cut out and the shields were driven into the caisson; they were then skidded through the caisson and driven out on the branch leading to Hoboken (Figs. 9), and when they reached the second switch enlargement, known as "caisson No. 2," the same procedure was followed, and driving was resumed northward on the line to Hoboken.

It was at first intended that these shields should be driven to the end of the iron-lined tunnel at the Hoboken terminus, but latterly it was decided to hasten the completion by installing two shields there and drive back to meet the former shields. These additional shields were started in January, 1907; and those of the westbound tunnel met on the 25th June and those of the eastbound tunnel on the 12th August, 1907.

The material encountered in the lower tunnel was partly a soft sandstone and partly sand and gravel with boulders; in the higher tunnel there was less rock and more sand, gravel and boulders, and a great deal of made ground, ashes and rubbish; and water had to be reckoned with throughout. At one place the tunnels passed through a mass of waste material from a gas-plant, which gave off a very disagreeable gas, with the result that a number of men were overcome and had to be carried out of the tunnel before they could be revived. These tunnels were largely under the tracks and terminal structures of the Delaware, Lackawanna and Western Railroad Company. No serious settlement or damage occurred. For a short distance on Ferry Street the tunnels were driven under the columns of an elevated railway, which were temporarily reinforced by wooden trestles while the shields were driven under. Permanent spread footings of concrete and steel were built thereafter, distributing the loads over a larger area and avoiding concentrated loads on the tunnel.

Simultaneously with the work in progress on the tunnels to

Hoboken, the tunnels on the remaining sides of the triangular junction were proceeded with (Figs. 9 and 10, Plate 2), from caissons No. 1 and No. 2, until the completion and working of the line from Hoboken to New York cut off access through these caissons to the tunnels, thereby suspending tunnelling until caisson No. 3 could be completed and work carried on from there. As before, the tunnels on the lower level were kept in advance of those on the higher level.

Tunnels E and F (Figs. 9 and 10) were completed by driving from caisson No. 3 until they met the short lengths previously driven from caisson No. 2. As the tracks for trains to Hoboken occupy the lower level of caisson No. 3 and the upper level of caisson No. 2, tunnel E, which is in the lower level of caisson No. 3, is in the upper level of caisson No. 2, tunnel F changing positions correspondingly.

New Jersey Connection of Up-town and Down-town Tunnels.

The lines connecting these tunnels were driven partly from Pier C shaft, which therefore was used jointly for these and the river-tunnels, and also from the "Washington Street shaft," in Washington Street, near Bay Street, Jersey City. For some distance from the river they were constructed in rock, without the use of compressed air, and were lined with concrete. Continuing from a point west of the Pennsylvania station, the tunnels extending to Summit Avenue, Jersey City, and those to Hoboken, form a Y, which are treated in a similar way to the junction between the up-town tunnels and the Hoboken line, level crossings being avoided by placing tunnels crossing each other on different levels (Figs. 17, 17a, and 17b, Plate 4). No unusual difficulties occurring in this section, it pursued its normal course of construction and therefore requires no further description.

Crossover and Switch Enlargements (Up-town Y).

As the enlarged section of tunnel required for switches at junctions could not be constructed with the standard tunnel-shields, and as the use of a special shield for the construction of the short lengths of tunnel involved would have been expensive, as would also construction by ordinary loose-ground hand methods, a special and novel plan of sinking concrete caissons, with switch and cross-over track accommodation within them, was carried out. As each

caisson varied in some particular feature, they are here separately described, being designated as caissons Nos. 1, 2 and 3.

Switch Enlargement, Caisson No. 1.—This enlargement, forming the junction of the up-town tunnels with those of the down-town system (Fig. 9c, Plate 2) previously referred to, was constructed as a monolith of reinforced concrete on the surface, and sunk to the level of the tunnel as a pneumatic caisson. In addition to the use of a shield, various other methods of building these enlargements were considered, one of which was to drive the shield past the location of the switch, break out the side of the tunnel, and excavate and timber by ordinary tunnelling methods. The objection to this plan was that it was not as safe as the one adopted, and that it would require a longer time to complete, as it could not readily be started until the tunnels were driven up to it. Another plan was to build by excavating from the surface, but this required very heavy, elaborate and expensive bracing to hold back the surrounding soil, as well as extensive pumping; moreover, the shields would be delayed in their passage until the structure had been completed and the excavation refilled. The great advantage possessed by the pneumatic-caisson method was that it permitted the work to be carried out in advance of the shields being driven to this point, and while some other method might have been carried out at less cost, the plan adopted could, with reasonable assurance, be executed whether the material encountered proved difficult or not.

The caisson as designed, with two chambers for the switches forming different floors, or stories, of the combined structure, was adopted only after careful consideration of plans for a separate caisson for each, sunk side by side, and requiring the excavation of a larger volume in passing from the surface to the required depth.

The caisson first designed was to be made of structural steel shapes with a skin of boiler-plates, all steel to be covered with concrete to protect it from corrosion and give the additional weight required in sinking. Tenders were asked for the steelwork required by this plan, but the shortest time quoted by the makers for the fabrication and delivery of the steel was 9 months, indicating that it would probably be a year before the caisson could be assembled ready for sinking. As it was desired to make much better progress than this, the subject was re-studied and a plan was developed for the construction of the caisson of reinforced concrete; and comparative estimates for the two plans, based in the first case on the tenders for structural steel, indicated that a saving of about £16,000 would be effected by the plan to use concrete reinforced with steel, which was therefore adopted.

The general design of caisson No. 1 is indicated in Figs. 9c, Plate 2. The main dimensions are:—

Length	101 feet $2\frac{1}{2}$ inches.
Width	{ 23 „ $5\frac{1}{4}$ „ to 45 „ 8 „
Height	51 „

The general arrangement of the steel reinforcing is indicated in the drawings. The structure was designed to resist not only the stresses it would be subject to in its final position but also the additional stresses during sinking resulting from the exterior forces and the air-pressure in the interior. The site was first surrounded by a platform supported by piles on which were placed the concrete-mixers, locomotive cranes, etc., and then excavated until the level of the water in the ground was reached. The steel cutting edge was then assembled in position, the forms were erected, air-locks were installed, and the lower half of the caisson was concreted; the excavation and sinking then commenced, using the whole interior of the lower level as a working-chamber. When the caisson had been sunk so that the top of the concrete was at about the level of the surface of the ground, sinking was stopped, additional forms were erected, and the upper half was concreted. Cylindrical steel shafts for access to the lower chamber were extended through the upper chamber, air-locks were placed on top, and sinking was resumed. When a depth was reached below which the caisson would sink no farther with its own weight, water was run into the upper chamber to provide additional weight. When the top had sunk below the surface of the ground the excavated material was deposited thereon, thus providing further weight and at the same time preventing the surrounding material from slipping into the excavation. The wooden forms for shaping the outside of the caisson were extended 4 feet 6 inches above the top so as to retain this material and form a line of cleavage between it and the surrounding material. The concrete forms, giving additional stiffness, were all sunk with the caisson, which was sunk until the cutting edge had reached a depth of 84 feet below the surface, or 77·2 feet below mean-tide level. Table II in the Appendix gives general data as to the weight of the caisson, skin-friction met with during sinking, and material passed through.

The total volume of material excavated was 10,700 cubic yards and the time required for sinking was 76 days. The hulls of two sunken canal-boats were encountered and had to be cut into pieces small enough to be taken out through the locks. When the caisson had been sunk to the proper depth the work was completed by closing the bottom with an inverted arch of concrete.

Switch Enlargement, Caisson No. 2.—Caisson No. 2 was of practically the same dimensions as caisson No. 1. It is situated farther from the river than No. 1, but is near a ship-canal, so that about as much water was encountered as in No. 1. The work was carried out in the same way as No. 1; no unusual difficulties were met with, and it was sunk to a depth of 90 feet below the surface, or 82 feet below mean-tide level.

Switch Enlargement, Caisson No. 3.—Caisson No. 3 (Figs. 9b, Plate 2) differed from Nos. 1 and 2 in several respects. Instead of having a wide and a narrow end, the two ends were similar in order to admit of a connection with additional tracks in the future. Its general dimensions are:—

Length	106 feet	5	inches.
Width	45 ,,	0	,,
Height	43 ,,	$11\frac{1}{2}$	,,

The cutting edge, instead of being placed at the tunnel-invert level, was placed at about the springing-line level, as test borings indicated that rock would be encountered before reaching the former level, thus making it unnecessary to sink the caisson deeper. It was completed by excavating the rock below and building the concrete invert and walls up to meet the portion sunk from the surface. The roof of this caisson, instead of being an arch as in the others, was made as concrete-steel trussing, at some saving in concrete, and afforded a more definite determination of the stresses.

In order to save the extra cost of compressed-air labour it was decided to sink the caisson as far as possible without air-pressure, removing the water by pumping, and in this way the caisson reached its final position without installing compressed air. However, the wisdom of designing it as a pneumatic caisson was proved when the Jersey City authorities simultaneously built a sewer which passed over the caisson to an outlet in the river near by; after the caisson was sunk and before the invert was sealed, this sewer was laid across the caisson, and the water from the river followed along the line of the sewer-trench and so saturated the material surrounding the caisson that air-pressure had to be installed to complete the invert. Air-pressure was also required while the plugs in the ends were being cut out to connect the various tunnels with the caisson.

Enlargement No. 4.—After caisson No. 1 had been completed it was found necessary to arrange so that an additional pair of tracks could be connected with the tunnels immediately west of this caisson. This rendered necessary the construction of an enlargement from the tunnel sufficient to admit of the placing of the junction switches and tracks when required.

Ninth Street Crossover Enlargement.—West of the Ninth Street station it was necessary to provide accommodation for a crossover switch, thus interrupting for a short distance the continuity of the two tubes and taking both tracks through a single chamber (Figs. 11, Plate 3). As the tunnels at this point were cast-iron tubes, the enlargement was built by driving the shields through and then breaking out of the tunnels, removing the segments, and excavating by soft-ground tunnelling methods, sufficient to build, first, concrete side walls, and secondly, a concrete arch spanning both tunnels, after which the iron tunnel-linings were removed, the material between was excavated, and a concrete invert was put in. The arch was built in sections about 15 feet in length, the overlying material being supported by steel I beams placed longitudinally, carried at one end in the completed arch and at the other by props extending down to the iron tunnel-lining. The material encountered was sand above, saturated with water, and rock below, and the work was executed under air-pressure.

Ninth Street—Sixth Avenue Junction.—This junction was built in a similar way to the Ninth Street crossover (Figs. 11). The westbound tube was driven from Christopher Street into Sixth Avenue and the eastbound tube into Ninth Street. Spaces were then mined for the supporting walls by breaking out of these tubes at various places. The space for the arches was then excavated, the arches were built, the iron lining was removed, the excavation completed and the invert laid (Figs. 11). The upper part of the work was in sand with rock below, air-pressure being used. On several columns of the elevated railway which were immediately over this junction, brackets were riveted and the loads were transmitted thereby on to large steel plate girders resting on the surface of the street, any settlement being corrected by wedges between the girders and the brackets. On completion of the underground work the air pressure was removed, pits were excavated under these columns and concrete piers were built up from the tunnel structure. The foot-passage leading to the Ninth Street station over this junction was also built by excavating from the surface after the air-pressure had been removed from the tunnel.

Stations.

Stations on Sixth Avenue and Forty-second Street Extension.—Three stations have been constructed in Sixth Avenue at the intersection of the following cross streets—Fourteenth Street, Nineteenth Street, and Twenty-third Street. They are all of similar design, and four

others are to be constructed—two-track stations at Twenty-eighth Street, Thirty-eighth Street, Forty-second Street and Fifth Avenue, and a three-track station at Thirty-third Street.

These stations were constructed in reinforced concrete by cut-and-cover methods in the same general way as the subway in Sixth Avenue, and in general they consist of a series of groined arches, supported by a partition-wall between the tracks, a row of cast-iron columns on each platform, and the side walls. Each station has two outside platforms, with a central length 18 feet 9 inches wide, and end lengths 10 feet wide. The entrances consist of stairways through adjoining shops or under stairs leading to the elevated railway stations above, and where they pass through shops, show windows are built into the side walls for the display of wares.

Ninth Street, Christopher Street and Erie Stations.—As these stations, of the same general type, depart somewhat in design from the general practice, a description of each will be given.

The first of these was built at Christopher Street. The work was executed by the following stages:—

1. Two standard ring tubes were driven through the length of the station 25 feet 6 inches apart between centres.

2. A chamber was excavated between the tubes by breaking out several segments in one of the tunnels, in which chamber a small roofed shield was erected and supported on the sides of the tubes.

3. This shield was driven through the length of the station, excavating the material between the tubes and supporting the roof with an arch of segmental cast-iron plates, the tubes being strengthened by temporary internal timber bracing and turn-buckle rods.

4. The segments on the inner sides of the tubes were removed and replaced with steel girders and columns; a concrete arch being then built inside the roof-segments and an invert between the lower girders.

This provided a station with an island platform, 16 feet 3 inches wide, within practically the same vertical limits as required for the ordinary tunnel tubes. The excavation was made in sand under compressed air (Figs. 12, Plate 3).

At the Ninth Street station a wider platform was desired, requiring the tubes to be spaced 27 feet 6 inches apart between centres, which gave a platform 18 feet 3 inches wide. The increased spacing of the tubes made the use of a roof shield for excavating between the tubes undesirable. The material, partly sand and partly rock, was excavated under compressed air by using poling-boards, supported by steel I beams placed at right angles to the

tunnel. Lengths for a pair of columns with girders were excavated, the sides of the tunnels were removed, the girders and columns were erected, and the concrete arch was built. The material under the tunnel being rock, the use of the girders under the columns, as at Christopher Street, was unnecessary (Fig. 11a, Plate 3).

The Erie station differed from the others in that the use of girders to support the roof between columns was avoided by using groined arches. This required the removal of a larger portion of the cast-iron tunnel previously built, but gave a much more roomy and pleasing appearance, the tunnels being 27 feet between centres, which gives a platform 17 feet 9 inches wide.

One iron-lined tube was driven continuously by shield to form one side of the station as usual, the other side was excavated and timbered, and the wall and half the arch were formed in concrete and temporarily supported by vertical posts. The material between was then excavated and timbered; the iron segments were removed from the side of the tube, the concrete arch was completed, the columns were erected, the groined arches springing from them formed in concrete, and the tube was suitably braced during operations (Figs. 13, Plate 3).

Hoboken Station.—This station is a three-track stub end terminal, adjoining the terminal station of the Delaware, Lackawanna and Western Railroad, and below the terminal of the Public Service Corporation street-railways. In order to avoid conflict of arriving and departing passengers, a central departure-platform is provided between the two main tracks, with arrival-platforms on the outer sides, so that the trains discharge on one side and receive passengers on the other.

Structurally, the station consists of a series of reinforced-concrete groined arches supported by cast-iron columns. The columns are spaced 15 feet apart between centres and the station-space is 88 feet by 381 feet 6 inches long. The arches have a rise of 4 feet throughout the main portion of the station, except a portion 90 feet long, where the rise is reduced to 2 feet to give headroom for an additional floor on which to distribute passengers to and from the street and the various platforms, to facilitate connection with the tramway-station on the surface, and to accommodate ticket-offices and other facilities. At the east end is a foot-passage connecting by stairs with the Delaware, Lackawanna and Western Railroad station. The north track is provided with an inspection-pit, the rails being supported on blocks of wood resting on concrete piers, whereby convenient access is afforded to the undersides of the trucks and motors of the trains.

The material excavated was partly river-silt and partly made ground; the station is supported by the underlying material only, and no piling or other artificial foundation was used. The underlying material consists of rock at the west end, clay in the centre and river-silt at the river end. The floor was reinforced so as to better distribute all loads over the area covered. Although some doubts were felt as to the possibility of excavating to the required depth so near the river in an open excavation, the work was completed without mishap. The surface over the site was largely covered with the tramways of the Public Service Railway Company, and these had to be supported and maintained during construction and restored on completion of the work. Over the western portion of the station two of the tramways ascend on an incline to an elevated structure, and the roof of the station had to be built to resist the heavy concentrated loads due to the columns of this structure. The eastern portion of the structure is in the Hudson silt near the river, and the thickness of the material covering the roof was so slight that additional weight had to be added by filling the space under the platforms solid with concrete to counteract the buoyancy due to the displacement. The sides of the excavation were supported by wooden sheet-piling, braced by struts extending from side to side. The station was waterproofed by surrounding the entire structure with an envelope of alternate layers of burlap and pitch of three to five ply.

At the western end of the station a lift was installed with which to transfer carriages between the underground tracks and the surface, where a repair-shop is situated.

Pennsylvania Station.—This station is situated immediately under the train-shed of the Jersey City terminus of the Pennsylvania Railroad. This train-shed is 778 feet long, and the roof consists of a steel arched truss of 252 feet 8 inches span. Although the tunnel station is close to the river and the rails are 71 feet below mean-tide level the rock in which the station was excavated was practically dry, very little water having to be pumped during construction. The station consists of two separate tunnels, each of 23 feet 6 inches span, containing a track and a platform 11 feet $4\frac{1}{2}$ inches wide. At the western end each tunnel branched into two, thus providing connections with the up-town and the Summit Avenue tunnels. In addition, a central dead-end tunnel was built, to enable trains crossing the river from New York to cross over for the return run. The entire station is lined with concrete (Figs. 17, 17a, 17b and 18, Plate 4).

A group of four lifts, each 9 feet 3 inches square, extends to the station of the Pennsylvania Railroad 92 feet above, and two

additional lifts, each 10 feet by 8 feet 6 inches, extend to the street-surface at Exchange Place; and the passages leading to these lifts are arranged so that passengers can enter the lifts on one side and leave on the opposite side, thus avoiding all conflict of arriving and departing traffic. The lifts are operated by direct hydraulic plungers. The power is supplied by electrically-driven hydraulic pumps placed in chambers prepared for them.

Some difficulty was experienced in sinking the shafts for these lifts. The one in Exchange Place is 23 feet wide, 39 feet long, and situated 200 feet from the river, where the depth to the surface of the rock is 33 feet. The space to be excavated was enclosed with steel sheet-piling driven to that rock, and when the lower part of the shaft was excavated the sheet-piling was found apart in places and somewhat distorted where it had met with obstacles, and there was more or less leakage. These leaks were overcome by pumping grout into the cavities, the excavation was completed, and the shaft was lined with concrete.

The shaft for the four lifts to the Pennsylvania Railroad station, Ferry Roadway shaft, was sunk with greater difficulty. It is situated immediately on the river's edge, is 21 feet wide and 62 feet long, and the rock is 44 feet below mean-tide level. Before sinking could commence, four columns supporting the structure of the railway-station, the foundations of which came within the area of the shaft, had to be supported temporarily by a wooden truss resting on clusters of piles outside the excavation. The same type of steel sheet piling as was used on the other shaft was driven to rock; owing to the limited headroom to the floor of the station above, it had to be driven in short lengths with a special pile-driver built for the purpose. As the excavation proceeded, timber braces were framed and set to hold the sheet-piling, but when a depth of 38 feet had been reached an inrush of water drove the workmen out. Soundings revealed the fact that the sheet-piling had been forced inwards by the pressure of the surrounding silt and water, with the result that it was decided not to take the risk of excavating the shaft further without air-pressure. The concrete lining of the shaft was then placed from a point 28 feet below to the surface, and was supported on piles driven to rock. An air-tight concrete floor was built and air-locks and air-pressure were installed, thereby completing the excavation without difficulty. When the sheet-piling was exposed it was found to have been forced inwards to such an extent as to prevent the construction of the concrete wall of sufficient thickness to withstand the outer pressure; it was there-

fore built of 10-inch steel joists placed 6 inches apart horizontally, with concrete between.

The surface of the rock was cleared and the concrete wall was sealed to it. Air-pressure was also installed in the chambers excavated around the site of the shaft in the rock below, and excavation was carried on from below upwards until a connection was made with the work from above, after which the concrete lining was completed.

Church Street Terminus.—The only station of the down-town system on the New York side is situated on the west side of Church Street, between Cortlandt Street and Fulton Street. This station is of sufficient size to accommodate not only the passengers carried by the pair of tubes crossing the river to the Pennsylvania Station but also the passengers to be carried in those to be built in the future to connect with the Erie Railroad. There are five tracks, a pair to be used ordinarily with each of the two services and one spare track. Each track has an unloading-platform on one side and a loading-platform on the other, thus separating the arriving from the departing passengers.

Owing to this station being only 1,000 feet distant from the point where the tubes cross under the river-wall, and where the invert is 55 feet below mean-tide level, the limitation as to the permissible gradient (apart from the requirements of the municipal authorities as to the depth of the tunnels below certain streets) necessitated the level of the rails in the station being 37 feet below the surface of Church Street, or 12 feet below mean-tide level. This depth enabled an intermediate floor to be constructed between the tracks and the streets to be used for waiting-rooms, luggage-rooms, booking-offices, etc., stairways to the platform below, and wide stairways and ramps leading to the street above being provided, the general arrangement of which was designed to separate incoming and outgoing passengers.

In designing stairways for the travelling public in New York, it has been found that with 7-inch risers and 11-inch treads the width handling a given number of passengers can be obtained by allowing 18 persons per minute per foot of width of stairway.

The high cost of land in this portion of New York rendered it desirable to obtain as great a return from the site as possible; therefore, an office-building twenty-two stories in height was built over the station. The boilers and machinery for heating, lighting, working lifts, and other facilities in such a building, require a large space, and as the first two floors below the street were required for the railway-station it was necessary to excavate an additional floor below the

tracks to furnish space for this machinery, as well as luggage-storage for the main-line railways. At the site of this terminus the general level of the surface of the rock is 78 feet below that of the street. Above the rock is a bed of hard-pan about 6 feet deep, and above this 47 feet of sand saturated with water. The elevation of the ground-water was about 15 feet below the street-surface, or 7 feet above mean-tide level in the river. The immense weight of a building of this height required that it should be founded on hard-pan or on rock, and the fact that three floors were required below the surface compelled the excavation of the entire site to hard-pan or rock. The fact that the bottom floor is 56 feet below the surface and 38 feet below the ground-water level, rendered it necessary that the basement floors should be enclosed with a wall impervious to moisture and of sufficient strength to withstand the pressure from the surrounding water and soil. The entire site was surrounded by more or less costly buildings, five to fourteen stories in height, none of which was founded on rock, which added to the difficulties, as did also the elevated railway along the Church Street side.

The building is of the structural steel-framed type common in America, in which the walls do not support any of the loads, but are themselves supported by the steel-work. The general design is indicated in Figs. 14 and 15, Plate 4.

The site is enclosed by a continuous concrete wall extending from the surface to the rock below and forming a dam to cut off the water from the interior. The site was first excavated to water-level, and the dam was built in monolith sections sunk from the surface in the form of pneumatic caissons. The wall is 8 feet thick and the sections were normally 30 feet long. The working air-chamber was 6 feet high at the sides and 7 feet 4 inches at the centre, and was formed of 4-inch plank held together by a frame of steel angles. Above the working-chamber the wall of concrete was built up as the caisson sank, the steel air-shaft extending from the working-chamber to the air-lock being embedded in the concrete. When the rock was reached, the surface was cleaned and levelled if necessary, the working-chamber and air-shaft being filled with concrete. The manner of making the dam continuous at the joints between adjoining caissons was as follows:—A semi-circular wooden form was placed in each end of a section of the dam, so that a cylindrical shaft lined with wood was formed between the concrete in adjoining caissons. After two adjoining caissons had been sunk a workman would start at the top, cutting out the wood in this shaft and caulking the small space between sections with wooden wedges and oakum, descending in this way until the solid concrete of the

working-chamber was reached, when the shaft was filled with concrete. In a few instances some difficulty was experienced where caissons moved slightly out of their true position in sinking, so that the two halves of the shaft were not exactly opposite, in which case it was necessary to fit an air-lock and install air-pressure.

As the dam-wall was not of sufficient strength to withstand the external forces without the assistance of the floors acting as struts, it was necessary to build each floor before the excavation could proceed to the floor next below, making it also necessary to install the interior columns with their foundations to the full depth before the floors could be built. The original plan was to sink pits in open excavation for these columns, after the surrounding water had been cut off by the completion of the main dam; but it was found the time required to sink the caissons forming this dam, seal them to rock and seal their joints, was such that the building would not be completed in time if the work were not carried on simultaneously with the interior columns. Therefore, the foundations for the interior columns were sunk as pneumatic caissons, circular in form, except a few which were situated so near to the dam that it was necessary to make them rectangular. These caissons consisted of wooden boxes held together with steel angles, with an air-floor 6 feet from the bottom and a cylindrical steel air-shaft extending from the air-floor to the air-locks at the top. In the caissons forming the dam the concrete generally provided sufficient weight for sinking, but in the interior caissons, with generally no concrete, sufficient weight was obtained by the use of cast iron. When the cutting edges of the latter reached hard-pan they were sunk no farther, but excavation was continued to the rock, where a base was put in of grillage-beams and concrete.

On completion of these foundations the first tier of columns was set, extending from the foundations to above the first floor below the street-surface, called the "concourse floor." The steel girders and beams forming this floor were then placed with the concrete between, thus forming a complete slab which prevented the wall from moving inwards under the pressure from without.

After the completion of the concourse floor the excavation was continued to the lower side of the track floor, and while this was proceeding the erection of the steel frame of the building continued above. The track floor was then put in, and excavation was resumed and continued until the sub-basement was reached.

An electrical sub-station for transforming the high potential current from the main power-house was placed in a portion of the basement, and had to be carried to a greater depth to provide

sufficient height for the machinery there, requiring the columns and foundations to be placed at a deeper level. All sand and loose material between the basement floor and the hard-pan was excavated and the space was refilled with cinders and broken stone, with underdrains leading to a sump, where ejectors were placed for removal of the seepage-water. The foundations under some of the columns had to support very heavy loads, as the grillages were designed to give a maximum pressure of 12 tons per square foot on the rock; the heaviest load on any one column is 1,540 tons. The erection of these columns involved the handling of heavy weights, some sections weighing 23 tons.

The following information regarding the sinking of these caissons may be of interest:—

Main Dam Caissons.

Number of caissons	51
First caisson started	31 July, 1906.
Last caisson completed	17 July, 1907.
Average time required for sinking	25·7 days.
Maximum ,, ,, ,,	57 ,,
Minimum ,, ,, ,,	11 ,,
Maximum size	30 ft. 0 in. by 8 ft. 0 in.
Minimum ,,	19 ft. 2$\frac{3}{4}$ in. by 8 ft. 0 in.

Interior Rectangular Caissons.

Number of caissons	32
First caisson started	22 December, 1906.
Last caisson completed	24 May, 1907.
Average time required for sinking	10·4 days.
Maximum ,, ,, ,,	29 ,,
Minimum ,, ,, ,,	3 ,,
Maximum size	15 ft. 3$\frac{3}{4}$ in. by 8 ft. 7$\frac{1}{2}$ in.
Minimum ,,	7 ft. 5$\frac{3}{4}$ in. by 7 ft. 4$\frac{1}{8}$ in.

Interior Circular Caissons.

Number of caissons	115
First caisson started	27 December, 1906.
Last caisson completed	22 May, 1907.
Average time required for sinking	10·5 days.
Maximum ,, ,, ,,	60 ,,
Minimum ,, ,, ,,	2 ,,
Maximum diameter	12 ft. 6$\frac{1}{2}$ in.
Minimum ,,	6 ft. 8 in.

The erection of the steel was commenced on the 10th January, 1907; the first tier of columns was completed on the 27th August, 1907; and the steel in the building was completely erected by the 23rd December, 1907: thus 348 days were required for the erection of

20,500 tons, occupying a height, from the lowest basement to the tower, of 381 feet 2 inches, and covering an area of $1\frac{3}{4}$ acre. The space enclosed by the building is 19,146,839 cubic feet, including 6,000,000 cubic feet below street-level. The offices in the building were occupied on the 1st May, 1908, although the space below, devoted to the railway-station, was not completed until later.

The building above the street-level and the architectural decorations below the street-level, were designed by Messrs. Clinton and Russell, architects. The building itself was erected under contract by the George A. Fuller Company, the structural steel being furnished by the American Bridge Company. The building and foundations below the street-level, involving much pneumatic work, were built under the general direction of the Author. The foundations were originally let by contract, but, owing to the contractor not making the required progress, the contract was cancelled and the work was taken over and completed by the railway-company's staff.

The approaches to this station, from the dam-wall to the beginning of the tubes in Cortlandt Street and Fulton Street, involved some difficult construction. Owing to the switches and curves, the shield method could not be used, the spreading tracks as they approach the station occupying practically the full width of the streets. The roofs of the tunnels are about 15 feet below the street-surface, and the entire structures are in very fine sand below the level of the water constantly present in the ground.

None of the buildings facing the streets where this work was to be executed had foundations extending below the level of the bottom of the tunnels, and before any actual construction work could be commenced it was necessary to underpin them. This was done by supporting the walls by needles and then forcing or jetting down steel pipes 10 inches and 12 inches in diameter, under the piers and walls supporting these buildings, to a firm bearing below the level of the tunnels.

This portion of the tunnel was constructed by first excavating all the material in the streets down to the level of the water in the ground, replacing the street-surface with temporary wooden platforms supported by steel joists resting on temporary wooden vertical timbers. The sewers and sub-surface pipes in the streets were either diverted to one side or suspended from these platforms. The structure forming the tunnel was built in sections in the space under the platforms and sunk in the form of pneumatic caissons of reinforced concrete to the required depth. Owing to the limited space available in which to build these caissons they could not be built to their full height at once, but were constructed as high as the

street-platforms would permit, then sunk until the walls were flush with the ground, and then built higher and the sinking resumed.

The tunnel in Cortlandt Street was sunk in sixteen sections and that in Fulton Street in seventeen sections. Each section was about 20 feet long. The sides of the caissons formed the permanent walls of the tunnels, but the ends were closed by temporary bulkheads during sinking which were cut out when adjoining caissons were sunk. The joints between caissons averaged 4 inches wide. In the floor the joints were sealed by placing concrete from the working-chamber of the caisson last sunk, and for the joints in the sides sheet piling was driven from the top, covering the joints outside, and then filled with cement grout pumped through pipes. The bulkheads were then removed, and the joints were scraped out and filled with cement mortar. The bulkheads were supported by a removable form of bracing so arranged that it could be used over again, and adjusted to the varying width of the caisson.

By the station building one side of the caissons abutted against the main dam-wall of the building and consequently had only one permanent side, and the floors and roofs had to be anchored to this wall. All roofs were constructed after the caissons had been sunk, and openings through the main dam-wall for the passage of tracks were cut out after the joints between it and adjoining caissons had been sealed to the wall.

Drainage and Ventilation.

Seepage-water is removed by pumps which are placed at the lowest points in the tunnels and are of the ordinary reciprocating type, driven by compressed air. The air is furnished by air-compressors located in the main power-house. In addition to working the pumps this air is used for the operation of a portion of the signal-system, and the line has valves provided at frequent intervals for working various pneumatic tools for track-repairs. The seepage in the portion of the tunnel longest in service has been 0·2 gallon per foot of single tunnel per hour.

Each track being in a separate tube the moving trains tend to maintain a current of air in a constant direction, and advantage was taken of this in designing a system of ventilation. Exhaust-fans for removing the air from the tunnels were placed at convenient points, fresh air being drawn in at the station stairways and shafts; and where these do not provide sufficient opening, they are supplemented by fresh-air blowers forcing air into the tunnels. The capacity of these fans is sufficient to supply about

30 cubic feet of fresh air per minute per passenger, during the maximum hour of traffic.

Permanent Way.—The permanent way consists of steel rails weighing 85 lbs. per yard, on timber sleepers bedded in broken stone ballast. Steel tie-plates are used between the rails and the sleepers. The rails are attached to the sleepers with screw spikes $\frac{7}{8}$ inch in diameter, and $6\frac{3}{4}$ inches long. On curves of 200 feet radius, or less, both rails are of rolled manganese-steel. On those 200 to 500 feet radius, the outer rail only is of manganese-steel, the inner rail being a special one of chrome-nickel steel.

Guard-rails are used on curves of less than 750 feet radius. These rails weigh 100 lbs. per yard and are $5\frac{3}{4}$ inches high, the height of the running-rail being $5\frac{3}{16}$ inches. Frogs and switches are also of manganese-steel. The gauge of the lines is 4 feet $8\frac{1}{2}$ inches. A complete section of the tunnel with the permanent way is indicated in Fig. 19, Plate 4.

A special design of permanent way was used in the Church Street terminal with the object of minimizing the vibration and noise in the building, and at the same time providing a track that could readily be kept in a clean and sanitary condition (Figs. 16, Plate 4).

On the portion of the up-town tunnels first opened to traffic Bessemer steel rails are used, but on the remainder of the tunnels the rails are of open-hearth steel of the following chemical composition (excepting where a special rail is used on curves as before mentioned):—

Carbon	0·75 to 0·90 per cent.
Phosphorus	0·03 per cent.
Silicon	Not over 0·20 per cent.
Manganese	0·70 to 1·00 ,,

Signalling.

Automatic block signals are installed throughout the system, designed to safeguard eight-car trains when running at intervals of $1\frac{1}{2}$ minute. The blocks are spaced on a double block overlap system in which a train is always protected by three block signals in the danger position and one block signal in the caution position. Automatic train-stop devices are placed at each block signal, arranged that if a train runs past a danger signal a tripper arm on the track engages a valve in the air-pipe on the carriages and applies air-brakes to the wheels. The lengths of the blocks are sufficient to allow braking distance to stop a train running past a signal at the maximum running speed with allowance for the gradient and alignment of the portion of the line under consideration, to which a further 25 per cent. is added as a safeguard.

Power-Plant for Construction.

Power for the construction of the tunnels was obtained from five main and three minor power-houses, which furnished compressed air at two pressures—one up to 50 lbs. per square inch for use in the tunnel-driving and in the working-chambers of caissons, and the other up to 125 lbs. per square inch for driving rock-drills, pumps, hoisting- and haulage-engines—and hydraulic power up to 5,000 lbs. per square inch for working the rams in the shields, and for electric lighting, as well as steam for driving-, hoisting- and haulage-engines, pumps, etc.

The following Table gives the capacities of the various plants :—

Plant.	Compressors. Capacity : Cubic Feet Free Air per Minute.		Hydraulic Pumps. Capacity : Gals. per Minute.		Generators. Kilowatts.	Boiler Horse-Power.	Indicated Horse-Power.
	High Air.	Low Air.	Pressure 5,000 Lbs.	Pressure 2,000 Lbs.			
Fifteenth Street .	6,726	8,954	60	..	80	1,800	3,330
Morton Street . .	4,741	5,040	40	..	40	1,200	1,930
Washington Street .	3,296	7,890	40	..	400	1,200	2,524
Pier C Shaft . .	4,400	5,550	40	..	450	1,800	2,110
Dey Street . . .	8,197	10,840	20	80	170	1,775	3,315
Hoboken Terminal .	..	..	..	..	..	455	..
Ninth Street . .	1,220	..	..	..	..	370	240
Railroad Avenue .	2,499	..	..	..	..	..	..
Total . . .	31,082	38,274	200	80	1,140	8,600	13,449

The plant for the cut-and-cover work in Sixth Avenue was furnished by the contractor. It consisted of electrically driven hoists and conveyors placed along the edge of the excavation, and rock-drills and pumps driven by compressed air. The compressed air was piped from a plant built for another work.

Work in Compressed Air.

A medical staff was maintained to give the workmen attention in case of accident or compressed-air sickness. No workmen were accepted for work in compressed air until after a physical examina-

tion by one of the medical staff, and only those were accepted who had the proper qualifications for work at the prevailing pressure on the section of the work under consideration.

Great care was exercised to maintain the air in the workings as pure as possible. Chemical analyses of the proportion of carbon dioxide in the air were made, and when the amount of fresh air pumped in to make good leakage was not sufficient to keep the amount of carbon dioxide below safe limits, air was drawn out and fresh air was pumped in.

The hours of work in compressed air were: for a pressure of 30 lbs. per square inch or less, one shift of 8 hours, which constituted a day's work; for a pressure of over 30 lbs., two shifts of 3 hours each, with an intermission of 3 hours, constituted a day's work. Work was carried on continuously throughout the 24 hours.

The Author is happy to state that, considering the magnitude of the work, its hazardous character, and the number of men employed, the fatalities have been few. When the work was proceeding at the maximum rate, 8,400 men were employed. From first to last 29,000 men have been passed by the medical staff for work in pressures over 20 lbs., and 11,400 men for work in pressure under 20 lbs. per square inch. There were 1,573 cases of compressed-air sickness sufficiently severe to require treatment, and but three deaths from this cause.

Railway Power-House and Rolling Stock.

Power-House.—The main power-house for working the railways is situated on the New Jersey side. The building is 214 feet by 192 feet. It is equipped with two 3,000-kilowatt and two 6,000-kilowatt turbo-generators. The turbines are of the Curtis type with vertical shafts, each supplied with a surface condenser. Condensing-water is obtained from the Hudson River through a tunnel 7 feet in diameter and 1,771 feet in length, the water being returned to the river by another conduit of equal area 1,088 feet in length. The boiler-plant consists of eight 900-HP. Babcock-Wilcox boilers, and there is space for eight more. The current is generated at 11,000 volts, three-phase, at which it is distributed to three sub-stations, and continuous current delivered from there to the contact rail at 600 volts.

Carriages.—Special steel carriages mounted on bogie trucks are used, of the following dimensions:—

Length over all	48 feet 3 inches.
Width	8 ,, 10 ,,
Height	12 ,,

Inflammable material is reduced to a minimum, the rattan in the seats and the leather straps to support standing passengers are the only things that are not of fireproof material: in the more recent type even the straps have been eliminated, by providing upright posts and longitudinal bars in place thereof. The floors are of cement on steel plates, with $\frac{1}{4}$ inch finish of carborundum cement. In order to facilitate the rapid loading and unloading of carriages they are provided with wide centre doors as well as side doors near the ends, with an unobstructed passageway between the carriage-platforms and the interior (Figs. 20, Plate 4). The doorways are provided with steel sliding doors supported by ball-bearing hangers, and are opened and closed by air-cylinders controlled by the guard with air-valves located at the ends of the carriages.

The carriages are equipped with Westinghouse electro-pneumatic automatic air-brakes of the most modern design, and each is supplied with an electrically-driven air-compressor with a piston displacement of 20 cubic feet of air per minute. In addition to the air-brakes, independent hand-brakes are provided.

A 70-volt storage-battery is provided on each carriage, furnishing power for auxiliary lights which remain lighted at all times, so that in the event of interruption of the power from the contact-rail the carriages still remain lighted.

The motor- and trailer-trucks are of the Master Car-Builder type and were built by the Baldwin Locomotive Works. The following are the general dimensions of the motor-trucks:—

Wheel-base	6 feet 6 inches.
„ diameter	$34\frac{1}{4}$ inches.
Tires, rolled steel	$5\frac{1}{4}$ „
Axles, hammered steel	6 inches in diameter at centre.
„ „ „	$6\frac{1}{2}$ inches in diameter at wheel-seat.

The wheels have cast-steel spoked centres and rolled-steel tires held on by double retaining-rings. One wheel on each axle has an extended hub upon which is shrunk the driving-gear.

The general dimensions of the trailer-truck are as follows:—

Wheel-base	5 feet 6 inches.
„ diameter	30 inches.
Tires	$5\frac{1}{4}$ „
Axles, hammered steel	$4\frac{3}{4}$ inches in diameter at centre.
„ „ „	$5\frac{3}{4}$ inches in diameter at wheel-seat.

One truck of each carriage is equipped with two 160-HP. "G.E. No. 76" motors. The Sprague-General Electric multiple-unit control is used. A hinged type of contact-shoe is used, which slides on top the of contact-rail. A protecting plank of jarrah, supported on wrought-iron brackets, is placed 4 inches above the contact-rail.

The weights of the carriages are as follows:—

Motor end without passengers	44,200 lbs.
Trailer ,, ,, ,, ...	30,350 ,,
Total weight ,, ,, ...	74,550 ,,
,, ,, with 100 ,, ...	88,550 ,,

The power-house, carriages and electrical equipment were installed under the direction of Mr. L. B. Stillwell, Consulting Electrical Engineer; Mr. Hugh Hazelton, Electrical Engineer; and Mr. John Van Vleck, Mechanical Engineer.

Surveys and Setting Out.

In the early days of the work the surveys, river triangulations and borings for the up-town and down-town tunnels were carried out separately, and the staff and equipment required were small; but as the work expanded a more comprehensive organization became necessary and was placed under three divisional engineers, reporting to the chief engineer through the principal assistant engineer. Each divisional engineer had his work subdivided into sections, each section under an assistant engineer with a staff of inspectors and assistants. During the period of maximum activity a staff of about 200 was employed on this work.

There have been in the tunnel-operations nineteen points where the tunnels have joined up, and, except in the old north tunnel, the maximum errors of surveys for holing through were $3\frac{1}{8}$ inches for line and $\frac{7}{8}$ inch for level, but most of the errors of level and line have been less than $\frac{3}{8}$ inch.

Cost.

The following figures of cost may prove of interest, exchange being at 4*s*. 1*d*. to the dollar.

The total cost of the project to date has been £12,000,000.

The $12\frac{1}{2}$ miles of single tunnel completed up to the present have cost about £6,000,000; this is for the tunnels complete with track, but without land, power-house, sub-stations, electrical equipment,

or rolling stock. The shield-driven, iron-lined, subaqueous tunnels averaged about £60 per lineal foot of single tunnel.

The cut-and-cover work along Sixth Avenue between stations cost about £120 per lineal foot of double tunnel.

The costs of the principal stations were:—

	£
Hoboken Terminal	136,000
Pennsylvania Station	127,000
Ninth Street ,, [1].	42,000
Christopher Street Station [1]	30,000
Erie Station [1]	39,000

The approaches to Church Street terminal, sunk as pneumatic caissons, cost £405,000. The large reinforced-concrete caissons forming the junction enlargements at the **Y** on the New Jersey side cost as follows:—

	£
Caisson No. 1	32,000
,, ,, 2	27,000
,, ,, 3	42,000

The following Table gives the approximate unit-cost and quantities of the principal items which entered into the work:—

	Quantity.	Approximate Unit Cost. £	s.	d.
Cast-iron tunnel-lining (tons of 2,000 lbs.) . . .	110,000	6	3	0
Cement (barrels of 380 lbs.)	750,000	0	6	5
Tunnel-bolts, with nuts and washers ($3\frac{3}{4}$ lbs. each) .	2,000,000	0	0	5
Broken stone (cubic yards)	288,000	0	4	0
Sand (cubic yards)	100,000	0	2	6
Dynamite (lbs.)	660,000	0	0	6
Coal, anthracite (tons)	210,000	0	16	0

Excavation in shield-driven tunnels under compressed-air cost 28*s.* to 52*s.* per cubic yard. On the cut-and-cover work on Sixth Avenue the excavation in earth cost 30*s.* per cubic yard and in rock 39*s.* The cost of concrete per cubic yard varied between 40*s.* and 60*s.* The cost of excavating the pneumatic caissons for the foundations of Church Street terminal building was £5 per cubic yard. The cost of the open excavation after water had been cut off by the surrounding dam-wall was 12*s.* per cubic yard.

[1] In excess of cost of tubes through the station.

Table III in the Appendix shows the total lengths of construction of different character.

The total quantities of the principal items handled in executing the work were:—

Excavation at normal pressure	598,000	cubic yards.
,, under compressed air	629,000	,, ,,
,, backfilled	131,000	,, ,,
Concrete	288,000	,, ,,
Brick masonry	20,000	,, ,,
Electric conduits	2,073,000	lineal feet.
Waterproofing	616,000	square feet.
Structural steel	30,000	tons [1]
Reinforcing steel in concrete	6,500	,, [1]

The wages paid the various classes of labour are given below:—

	Daily Rate.	Hours constituting a Day.
In normal pressure:—	£ s. d.	
Labourers (per hour)	0 0 7½	..
General foremen	0 16 0	12
Foremen	0 10 0 to 0 14 0	10
Blacksmiths	0 14 0	10
Pipe-fitters	0 10 0 to 0 14 0	10
Machinists	0 10 0 to 0 14 0	10
Carpenters	0 12 0	10
Under compressed air:—		
Caisson foremen	1 0 0	12
,, sub-foremen	0 14 0	8
,, lock-tenders	0 10 0	8
,, labourers	0 10 0	8
Shield Tunnels:—		
General foremen	1 0 0	8
Miners	0 12 0	8
Helpers	0 10 0	8
Muckers	0 11 0	8
Pipe-fitters	0 12 0	8
Lock-tenders	0 9 0	8

[1] Tons of 2,240 lbs.

Reinforced Concrete.

A marked feature of the work was the general use of concrete and reinforced concrete, not only as a substitute for brick and stone masonry, but also in place of steel girders and beams. The latter material was found economical, its use permitting great flexibility in design and speed in execution; and it is especially suited to a structure underground where it is not subject to the action of frost and extremes of temperature.

The following unit-stresses were used in reinforced-concrete design:—

	Working-Stress.
Beams :—	
Concrete in compression	500–600 lbs. per square inch.
,, ,, shear, average stress—	
(A) Without shear reinforcement .	30–40 ,, ,, ,, ,,
(B) With ,, ,, . .	50–80 ,, ,, ,, ,,
Bond Stress :—	
(A) Smooth rods	60–75 ,, ,, ,, ,,
(B) Deformed rods	100–175 ,, ,, ,, ,,
Steel, in Tension	16,000 ,, ,, ,, ,,
Ratio between modulus of elasticity of steel and concrete	12–15
Columns :—	
Concrete in compression	300–400 lbs. per square inch.
Ratio between modulus of elasticity of steel and concrete	15–20

The reinforcement consisted mainly of 1-inch-square twisted rods.

Stability of Tunnels in Silt.

The general nature and extraordinary character of the Hudson River silt was demonstrated in the early efforts to build the tunnel, and, in fact, most of the difficulties were due to the unusually mobile and quasi-fluid nature of this material, which will actually flow freely through a small hole in the lining. When work on the construction of these tunnels was resumed, the question of their permanent stability under working conditions was given the most careful consideration, and, in view of the character of the equipment, which was to consist of multiple-unit trains similar to those used on the London underground railways with no heavy loads concentrated on the wheels, it was concluded that the surrounding bed of silt had sufficient stability and bearing-power to maintain the tunnels in equilibrium.

At about the time that work was resumed on these tunnels under the direction of the Author, he was also appointed Chief Engineer of the Pennsylvania Railroad Company's extension by tunnels under the Hudson River into New York. The conditions here were essentially different, involving instead of the comparatively light multiple-unit trains to be used in the Hudson and Manhattan tunnels, the support of the concentrated live loads due to the use of heavy electric locomotives and the heavy sleeping-, dining- and mail-carriages of the Pennsylvania Railroad.

In the light of the available knowledge as to the stability of the Hudson River silt, and in view of no precedent existing for the construction of a tunnel to carry such heavy moving loads in such a soft material, a scheme was devised by the Author, and was approved by the management of the Pennsylvania Railroad, to carry the railway track and live loads independently of the tunnel-lining, on piers sunk from the tunnels through the silt to the underlying rock, the chief object being to protect the tunnel shells from vibration which might puddle the silt and lead to disturbing their stability. These tunnels were therefore constructed with a view to installing these piles, or piers, 15 feet apart between centres if required.

In the meantime, while construction was progressing on the tunnels of both projects, constant observations were made to record the behaviour of the tunnels during and after construction, and experiments and investigations as to the supporting-power of the silt and the resulting pressures on a tunnel-lining constructed through it, were continued.

Generally speaking, the average subsidence of the tunnels after construction was about 3 inches, and in the process of driving a shield alongside an already constructed tunnel it has been known to throw the other tunnel over laterally to the extent of 5 inches, even when taking in 40 per cent. of ground.

The up-town tunnels described in this Paper have been in service now for, in all, 24 months, and observations extending over this period appear to indicate that no movement has taken place. The behaviour of the tunnels while under construction leads to the conclusion that the movements for some time after are due to the resilience of the ground, if such it may be termed, the tunnels which were thrown laterally out of position having now gradually returned almost to their original positions. The weight of the silt in its natural state, containing about 38 per cent. of water, is about 103 lbs. per cubic foot, and, if London clay were mixed with, say, 30 per cent. or more of water in a pug-, or mortar-mill, a very fair repre-

sentation of Hudson River silt would be obtained. Judging the problem of stability solely on the basis of the weight of the tunnel-structure and the weight of the silt it displaces, there may seem to be as much, or even more, reason to presume the tunnels might go up than that they might go down. While the tunnels did rise slightly immediately in the rear of the shield during construction, on the other hand, they steadily and certainly subsided, making allowance for a slight distortion, to the average extent of almost 3 inches. This occurred during the period when experiments were being carried out within the tunnel, also while the tunnel lay idle, and, finally, while the concrete lining was being placed, covering in all a period of about 30 months. The numerous operations within these tunnels during this period, when compressed air was repeatedly taken off, no doubt prolonged this period of subsidence.

Finally, on the problem being very carefully considered and studied, the conclusion was arrived at that sufficient reliance could be placed on the considerable inertia of the Pennsylvania tunnels—due largely to the exceptionally heavy internal lining of concrete—to obviate the immediate necessity of the above-mentioned piers, the sinking of which has consequently been suspended.

Another matter of considerable interest and importance in connection with the question of the use or non-use of pile foundations, was the rise and fall of the tunnels with the tide. Under the average tide (4 feet) they moved 0·01 foot and, with a maximum range of tide (10 feet) a vertical change of position of fully 0·02 foot occurred; they rose at low tide and fell at high tide. In view of the minute differences of elevation of these tunnels which it has been possible to record, it may be well to explain that though ordinary levelling instruments were used continually for this purpose, they were much more than verified by observations on bench marks or steel rods passing through the bottom of the tunnel down into bed rock. In one case the steel rod (within a steel-pipe casing), extended down to bed rock, a depth of 214 feet below the tunnel. Very accurate readings could, of course, be taken by a direct vernier method, giving the variation of elevation of the tunnel relatively to these steel rods, which projected through stuffing-boxes in the bottom of the tunnels. In addition to this, the relative displacement was measured by a continuous recording-apparatus, a recording tide-gauge, connected by a pipe with the river above, giving simultaneous diagrams of the state of the tide.

Opening of the Tunnels for Traffic.—The working of trains through the up-town tunnels from Hoboken to Nineteenth Street station, New York City, was commenced on the 25th February, 1908, and

on the 15th June, 1908, the traffic was extended to Twenty-third Street station, New York City.

The down-town system of tunnels between Church Street terminal, New York City, and the Pennsylvania station, Jersey City, was opened to traffic on the 19th July, 1909.

The connection from the Pennsylvania station to the Erie station, and from there on to either the Hoboken terminus, or direct to the up-town stations in New York City, was completed for use on the 2nd August, 1909.

ORGANIZATION AND STAFF.

A work of this magnitude required an extensive organization. The staff was divided into two main departments—engineering and construction. The engineering department was charged with the design, survey, inspection, setting-out, estimates, records, etc. The construction department was charged with the actual direction of the workmen, the ordering of the material and supplies, the working of the power-plants, etc.

The engineering and construction staffs reported to the Author as Chief Engineer, and to the Deputy Chief Engineer, Mr. J. Vipond Davies, M. Am. Soc. C.E.

The duties of the engineering department devolved upon Messrs. George D. Snyder, M. Am. Soc. C.E., Principal Assistant Engineer, and T. B. Whitney, Jun., Assoc. M. Am. Soc. C.E., Engineer of Design; also on three Divisional Engineers—Messrs. F. K. Hilt, H. G. Burrowes, M. Am. Soc. C.E., and A. R. Archer, Assoc. M. Am. Soc. C.E.

The construction department was placed under the charge of four Works Managers—Messrs. Reginald S. Courtney, Vivian Messiter, H. F. D. Burke and Charles J. Crowley.

The thanks of the Author are extended to these officers and their forces for the zeal and accuracy with which they carried out the work.

The Paper is accompanied by tracings, from which the illustrations in Plates 2–4 have been prepared.

[APPENDIX.

APPENDIX.

TABLE I.—RECORDS OF SHIELDS.

Shield No.	Where Used.	Diameter. Ft.	Diameter. Ins.	Length of Tunnel Built.	Time in Use. Days.	Remarks.
0	North tunnel	19	11	1882, Pearson. 1625, Huds. Imp. Co.	373 505	Independent erector. Hinged doors.
1	South ,,	17	0	5,206	704	Attached erector, hinged doors. (See 9.)
2	West-bound New York approach	17	0	4,524	1,394	,, ,, ,, ,,
3	East- ,, ,, ,, ,,	17	0	3,882	744	Independent erector, slat doors.
4	Fulton Street tube from Jersey	17	0	4,271	1,200	,, ,, ,, ,,
5	Cortlandt Street tube from Jersey	17	0	5,005	1,150	,, ,, ,, ,,
6	South tube, Hoboken approach from river	17	0	1,946	622	,, ,, ,, ,,
7	North ,, ,, ,, ,, ,,	17	0	1,658	451	,, ,, ,, ,, (See 17.)
8	Fulton Street tube from New York	17	0	1,705	618	,, ,, ,, ,,
9	North-bound Washington Street	17	0	3,375	737	,, ,, ,, ,, Reconstructed from 1.
10	S. tube, Hoboken approach from Hoboken	17	0	1,189	206	Independent erector, slat doors.
11	N. ,, ,, ,, ,, ,,	17	0	989	160	,, ,, ,, ,, (See 18.)
12	East-bound 6th Avenue	17	0	757	203	,, ,, ,, ,,
13	Tunnel "C"	17	0	669	659	,, ,, ,, ,,
14	No. 2 West Railroad Avenue	17	0	297	87	,, ,, ,, ,,
15	Fulton Street Erie	17	0	204	35	Remaining to centrings.
16	Cortlandt Street, from New York	17	0	881	492	,, ,, ,,
17	,, ,, Erie	17	0	94	15	,, ,, ,, Reconstructed from 7.
18	Dey Street, Foot Passage	17	0	..	..	,, ,, ,, ,, ,, 11.

Aggregate length, 40,159 feet = 7·61 miles.

Table II.—Record of Sinking Caisson No. 1.

Observations taken at 8 a.m.

In this Table the reaction due to air-pressure is calculated on the assumption that it acts on the whole area inside the cutting edge, whether excavated or not.

The weight of the concrete includes that of all timber forms and lagging, and of all metal-work built in. The net weight is obtained by deducting the reaction due to air-pressure, after adding the weight of the air-locks and shafts, etc., and also of the water-ballast. This last was first used on 8th April, commencing at 500,000 lbs., and increasing to a final maximum of 11,000,000 lbs. as the work progressed.

With the caisson in its final position on 7th June, the weights were as follows:—

	Lbs.
Concrete	13,626,000
Air-locks, shafts, etc.	120,000
Water-ballast	11,150,000
	24,896,000
Reaction due to air-pressure	12,861,000
Net weight	12,035,000

Date. 1906.	Total Sinkage to Date. Ft.	Ins.	Depth Immersed. Feet.	Weight of Concrete. Thousands of Pounds.	Net Weight. Thousands of Pounds.	Surface in Contact. Sq. Ft.	Average Skin-Friction. Lbs. per Sq. Ft.	Material.
March 8	17	6¼	20·9	6 805	2,899	5,760	503	Silt
„ 13	17	7⅛	20·9	7 158	3,252	5,760	565	„
„ 14	17	7¼	20·9	7 158	3,252	5,760	565	„
„ 15	17	7¼	20·9	7,158	3,252	5,760	565	„
„ 16	17	7¼	20·9	7,158	3,252	5,760	565	„
„ 17	17	8⅛	21·0	7,758	3,852	5,793	665[1]	„
„ 18	19	2½	22·6	8,658	4,258	6,206	686	„
„ 19	19	10½	23·2	9,538	4,643	6,382	727	„
„ 20	20	3⅝	23·7	9,820	4,925	6,495	758	„
„ 21	20	7½	24·00	10,666	5,771	6,583	877	„
„ 22	21	3⅝	24·71	11,442	6,547	6,759	969	„
„ 23	21	5⅛	24·80	12,292	6,902	6,796	1,015	„
„ 24	21	6⅜	24·90	12,702	6,818	6,822	999	„
„ 26	21	10¾	25·30	13,626	7,742	6,920	1,119	„
„ 27	21	11⅛	25·30	13,626	7,766	6,928	1,121	„
„ 29	22	6½	25·90	13,626	7,271	7,080	1,027	„
„ 30	23	11⅛	27·30	13,626	6,777	7,444	911	„
„ 31	24	2¼	27·50	13,626	6,282	7,515	836	Silt with some sand
April 1	25	10	29·20	13,626	6,777	7,947	853	
„ 2	26	0¼	29·40	13,626	6,282	7,997	786	Silt mixed with sand, boulders at west end
„ 3	27	1¾	30·5	13,626	5,540	8,289	668	Silt, sand and small boulders
„ 4	29	6⅞	32·9	13,626	5,293	8,929	593	

[1] This figure for friction is not really true, since the walls of the caisson are sinking into the silt without any excavation being made.

TABLE II—*continued.*

Date. 1906.	Total Sinkage to Date.		Depth Immersed.	Weight of Concrete.	Net Weight.	Surface in Contact.	Average Skin-Friction.	Material.
	Ft.	Ins.	Feet.	Thousands of Pounds.	Thousands of Pounds.	Sq. Ft.	Lbs. per Sq. Ft.	
April 5	31	2¼	34·5	13,626	7,271	9,356	777[1]	Hard pan.
,, 6	32	7¼	35·9	,,	7,024	9,728	722[2]	,,
,, 7	33	9⅜	37·1	,,	6,282	10,038	626	,,
,, 8	35	0	38·3	,,	7,029	10,357	679	,,
,, 9	35	3	38·6	,,	6,287	10,423	603	,,
,, 10	35	3	38·6	,,	6,287	10,423	603	,,
,, 11	35	3	38·6	,,	6,287	10,423	603	,,
,, 12	37	6⅞	40·9	,,	5,545	11,035	502	,,
,, 13	37	6⅞	40·9	,,	5,745	11,035	520	,,
,, 14	39	10	43·2	,,	5,498	11,627	473	,,
,, 15	39	10	43·2	,,	5,498	11,627	473	,,
,, 16	40	11¾	44·3	,,	5,998	11,929	502	,,
,, 17	40	11¾	44·3	,,	6,698	11,929	562	,,
,, 18	43	1⅜	44·3	,,	6,203	11,939	520	,,
,, 19	43	1⅜	46·5	,,	6,203	11,930	520	,,
,, 20	44	4⅛	47·7	,,	6,681	12,817	520	,,
,, 21	45	3¼	48·6	,,	6,681	13,062	511	,,
,, 22	45	3¼	,,	,,	6,686	13,062	511	,,
,, 23	45	3¼	,,	,,	6,686	13,062	511	,,
,, 24	46	8⅛	50·6	,,	6,697	13,432	498	,,
,, 25	47	3⅝	50·6	,,	5,966	13,603	439	,,
,, 26	47	11¾	51·3	,,	5,480	13,773	398	,,
,, 27	48	10½	52·2	,,	5,480	14,010	391	,,

[1] Gravel and coarse sand at west end, fine sand in centre, silt and sand east end.

[2] Gravel at west end, hard-pan in centre, sand and silt at east end.

TABLE II—*continued.*

Date. 1906.	Total Sinkage to Date.		Depth Immersed.	Weight of Concrete.	Net Weight.	Surface in Contact.	Average Skin-Friction.	Material.
	Ft.	Ins.	Feet.	Thousands of Pounds.	Thousands of Pounds.	Sq. Ft.	Lbs. per Sq. Ft.	
April 28	49	5$\frac{5}{8}$	52·7	13,626	5,480	14,149	387	Hard pan.
„ 29	50	0$\frac{7}{8}$	53·4	„	5,566	14,320	389	„ „
„ 30	51	2$\frac{3}{8}$	54·6	„	6,636	14,638	453	„ „
May 1	52	7$\frac{1}{8}$	56·0	„	7,172	15,000	478	„ „
„ 2	54	2$\frac{3}{4}$	57·6	„	7,465	15,435	484	„ „
„ 3	55	4	58·7	„	7,712	15,726	490	„ „
„ 4	55	4	58·7	„	7,712	15,726	490	Hard pan with soft sandstone.
„ 5	57	0$\frac{3}{8}$	60·4	„	7,218	16,175	447	„ „
„ 6	57	0$\frac{3}{8}$	60·4	„	7,218	16,175	446	Soft sandstone.
„ 7	57	0$\frac{3}{8}$	60·4	„	7,547	16,175	466	„ „
„ 8	57	0$\frac{3}{8}$	60·4	„	7,861	16,175	486	„ „
„ 9	59	0$\frac{3}{4}$	62·4	„	8,852	16,709	529	„ „
„ 10	59	0$\frac{3}{4}$	62·4	„	9,192	16,709	550	Soft and hard sandstone.
„ 11	61	1$\frac{5}{8}$	64·5	„	8,865	17,254	551	„ „
„ 12	61	1$\frac{5}{8}$	64·5	„	9,313	17,254	540	„ „
„ 13	61	1$\frac{5}{8}$	64·5	„	9,613	17,254	557	„ ,
„ 14	63	2$\frac{5}{8}$	66·6	„	9,813	17,803	557	„ „
„ 15	63	2$\frac{5}{8}$	66·6	„	10,124	17,803	568	„ „
„ 16	65	6$\frac{1}{8}$	68·9	„	10,694	18,405	581	„ „
„ 17	65	6$\frac{1}{8}$	68·9	„	10,714	18,405	582	„ „
„ 18	65	6$\frac{1}{8}$	68·9	„	10,734	18,405	583	„ „
19	67	11$\frac{1}{8}$	71·3	„	10,754	19,044	565	„ „

TABLE II—*continued.*

Date. 1906.		Total Sinkage to Date.		Depth Immersed.		Weight of Concrete.	Net Weight.	Surface in Contact.	Average Skin-Friction.	Material.
		Ft.	Ins.	Ft.	Ins.	Thousands of Pounds.	Thousands of Pounds.	Sq. Ft.	Lbs. per Sq. Ft.	
May	20	67	$11\frac{1}{8}$	71	3	13,626	10,754	19,044	565	Soft and hard sandstone.
,,	21	,,	,,	,,	,,	,,	10,774	,,	565	,, ,,
,,	22	,,	,,	,,	,,	,,	10,794	,,	567	,, ,,
,,	23	,,	,,	,,	,,	,,	10,814	,,	568	,, ,,
,,	24	70	$3\frac{3}{4}$	73	7	,,	10,520	19,674	534	,, ,,
,,	25	,,	,,	,,	,,	,,	10,745	,,	546	,, ,,
,,	26	,,	,,	,,	,,	,,	10,970	,,	557	,, ,,
,,	27	70	$3\frac{3}{4}$	73	7	13,626	11,995	19,669	610	,, ,,
,,	28	72	$11\frac{1}{8}$	76	3	,,	11,725	20,356	576	,, ,,
,,	29[1]	,,	,,	76	3	,,	11,478	20,356	564	,, ,,
,,	30	,,	,,	,,	,,	,,	,,	,,	,,	,, ,,
,,	31	,,	,,	,,	,,	,,	"	,,	,,	,, ,,
June	1[2]	,,	,,	,,	,,	,,	11,628	,,	571	,, ,,
,,	2	,,	,,	,,	,,	,,	11,530	,,	566	,, ,,
,,	3	,,	,,	,,	,,	,,	11,680	,,	574	,, ,,
,,	4	,,	,,	,,	,,	,,	11,830	,,	581	,, ,,
,,	5	74	$11\frac{1}{8}$	78	3	,,	11,985	20,888	574	,, ,,
,,	6	,,	,,	,,	,,	,,	12,035	,,	576	,, ,,
,,	7	76	$10\frac{3}{8}$	80	2	,,	,,	21,396	562	,, ,,

[1] Strike of labourers.
[2] Strike ended.

TABLE III.—TOTAL LENGTHS (IN FEET) OF CONSTRUCTION OF DIFFERENT CHARACTER.

	Brick Section	Iron 19 Feet 5¼ Inches.	Iron 16 Feet 7 Inches.	Iron and Concrete.	14-Inch Arch Concrete.	Circular Concrete.	Cut and Cover.	Caisson Con-struction.	Station Construction.		Enlarge-ments.
									Iron Rings.	Concrete Arch.	
Hoboken terminal	..	..	..	..	..	..	592	..	..	..	..
East-bound, Hoboken to 27th St.	..	..	11,974	..	..	..	2,782	173	700	1,073	182
West-bound, ,, ,, ,, ,,	1,977	3,507	6,479	..	..	..	2,782				
Ninth Street, east-bound	..	..	150	..	..	..	..	..	..	..	8
Tunnel "C"	..	..	582	278	..	..	..	..	..	..	87
,, "D"	..	..	391	345	..	102	..	..	..	..	..
,, "E"	..	..	134	..	1,127	..	..	..	..	..	..
,, "F"	..	..	..	548	709	..	..	..	..	..	..
North-bound, Washington St.	..	..	2,956	..	1,748	..	..	106	216	..	217
South-bound, ,, ,,	..	..	..	..	4,818	..	..	..	..	216	163
Track No. 1 West	.	..	..	..	454	..	..	..	..	..	..
,, ,, 4 ,,	..	..	..	..	684	..	..	..	..	..	..
,, ,, 2 ,,	..	..	297	..	1,051	..	..	..	..	..	..
,, ,, 3 ,,	..	..	..	..	1,071	..	..	..	..	..	..
,, ,, 5 ,,	..	..	..	..	366	..	..	..	..	..	54
Pennsylvania Station	..	..	..	..	..	..	..	..	..	798	..
East-bound, Penn. Sta. to Church St.	..	..	5,886	..	..	..	..	..	..	..	20
West-bound, ,, ,,	..	..	5,976	..	..	..	..	..	..	..	..
Erie tube, Cortlandt Street	..	..	94	..	..	..	..	..	..	..	..
,, ,, Fulton Street	..	..	204	..	..	..	..	..	..	..	..
,, crossing, east-bound	..	..	54	..	..	..	..	..	..	..	..
,, ,, west-bound	..	..	140	..	..	..	..	..	..	..	..
Church St. terminal to caissons	..	..	..	..	..	..	..	1,057	..	..	..
Totals	1,977	3,507	35,317	1,171	12,058	102	6,156	1,336	916	2,087	731

Grand total of all construction = 65,358 feet = 12·38 miles.

Discussion.

The President, in moving a vote of thanks to the Author for his valuable Paper on a very remarkable work, observed that the members were fortunate in having the Author present. Perhaps half the works described in the Papers dealt with by The Institution were executed abroad, and it was not often that the Authors of such Papers could be present when they were discussed. The communication before the meeting was really a notable addition to the records of The Institution. The Author had described in a matter-of-fact way for the first time the "simple" operation of driving a tunnel through slurry; he dignified the material with the name of silt, but the President thought that if London clay were mixed with 30 per cent. of water, "slurry" would more nearly describe its condition, and in the discussion that circumstance should not be forgotten. He was delighted to think that the Author was a Member of The Institution. The President

The Author, after exhibiting a series of slides illustrating some features of the work and some of the difficulties met with in carrying it out, remarked that the working of the lines through the four tunnels had been entirely successful, because in January, 1910, 4,180,000 people were carried, equivalent to upwards of 50 millions a year. There was no doubt that when the extensions were finished the railways would certainly carry in the first year at least 80 million passengers. Therefore the utility of the tunnels was well demonstrated by the traffic, and the working of the ferry-boats would, he thought, be a matter of history in a very short time, as far as passenger-traffic was concerned. For vehicular traffic the ferry-boats would no doubt continue to be used until highway-tunnels were built, and he believed that in the future such tunnels would be built, joining up still further the State of New York and the State of New Jersey—or, in other words, the entire United States. He thanked the President very much for his courteous expression of approval of the Paper, and only hoped his communication would prove useful to the profession. The Author.

Mr. E. W. Moir observed that the Paper was of peculiar interest to him, owing to the fact that 20 years ago he struggled with the problem himself, under the late Sir Benjamin Baker, Past-President Inst. C.E. There were several points of historic interest not dealt with in the Paper, and he thought it would be useful to record the Mr. Moir.

Mr. Moir. doings of those who went before the Author, who had so very ably carried the scheme to successful completion. The Hudson tunnel was the first tunnel in which compressed air was used to hold back slurry or silt and water in strata through which it percolated, a system invented by Admiral Cochrane, afterwards Lord Dundonald, and patented by him in 1830. A great debt was owing to Admiral Cochrane for many things, and especially, on the part of engineers, for his invention of the compressed-air system of tunnelling. Another name that should be mentioned was that of Dewitt Clinton Haskin, a man from the Western States of America, who, having made a few railways there and acquired some money, came to New York and conceived the great project of tunnelling under the Hudson River to connect New York City direct with the west-going railway-systems. He began sinking his shaft on the New Jersey shore in 1874, and started from the side of the shaft to mine in the silt with the aid of compressed air. Not being an expert engineer, he had an idea that painted canvas laid upon the silt would maintain it in position. With him was a very able superintendent, a Swede named Anderson, who told Mr. Moir that he had great trouble in inducing Haskin to give him sufficient timber to support the silt, Haskin thinking that the painted canvas and the effort of the air to get out through the silt afforded ample provision for holding up the material. Owing to that idea and other causes there was a disastrous accident, Anderson only escaping with his life and a good many men being engulfed. A caisson was sunk over the place where the excavation fell in, and ultimately the bodies were recovered and the work went boldly ahead again, with shored iron plating. It advanced at a speed of 18 inches to 3 feet per day by a system of plating, chopping out the silt, and lining the plating with 18 inches to 2 feet of brickwork. Later on the silt became softer, and Anderson invented the pilot system of tunnelling, which consisted in the use of a tube built of plates, 6 feet in diameter and 50 to 60 feet long. This enabled them to go about 2,000 feet, and they might perhaps have gone farther. The tube was built ahead of the exposed larger face, and the tail end of it was strutted against completed brickwork behind. The effect of the tube was to reduce the area of the exposed face: further, by means of fins placed through the joints of the plating, the tube was enabled to hang on to the unmined silt, so that the horizontal thrust of the moving silt could be controlled more or less, and radial struts were placed from the outside of the pilot to the thin plating which was put next to the exposed earth, like the spokes of a wheel. By that means a considerable length of tunnel was built at an average speed, while working, of 18 inches per day.

Mr. Moir. Through all sorts of vicissitudes, such as lack of money, lack of sympathy from anybody—the railway-companies would not listen to the idea of its being any advantage to them—Haskin had managed to construct this pioneer work when he was brought to an absolute stop, in 1888, by want of funds and frequent collapses of his heading. Then, at the instigation of some English financiers, Sir Benjamin Baker paid a visit to the tunnel. He was greatly impressed with the possibilities of the scheme as a whole and its capacity to bear the cost of construction and ultimately become a paying concern. Incidentally, in the course of his examination, he was nearly locked in the tunnel himself. He went into the heading with Haskin's nephew, and on coming out they found it impossible to shut the inner lock-door and make it air-tight. When they opened the valve to let the air out of the intermediate chamber, between the two doors, the leaks on the inner door were so serious that they could not get the pressure reduced between the doors, in order to open the door that would lead them into the ordinary atmosphere. For a long time they were afraid that they would not get out, but they smeared the inner door with mud, and at last managed to get the pressure slightly reduced so that the air squeezed the inner door more tightly to its frame, and after a considerable time they managed to escape, fortunately for the world. Haskin continued for a short time after Sir Benjamin Baker made his Report in 1888, in which report Sir Benjamin staked his reputation on the completion of the work—a very bold thing to do for a man who had so great a reputation to lose. Financial arrangements were completed, a contract was prepared and let to Messrs. S. Pearson and Sons, and Mr. Moir was entrusted with the design of the shield under Sir Benjamin Baker's directions, while he was still at the Forth Bridge. He designed the shield which ultimately, as Mr. Jacobs had informed him, got across the river and finished the North tunnel. He went out to New York as Resident Engineer, but was transferred to the contractors for political reasons in January, 1890. At that time there was about 200 to 250 feet of the tunnel built beyond the last bulkhead, and Haskin had had three collapses in 100 feet. The tunnel was full of something worse than slurry, the pilot-tube was askew across the tunnel, and there was a hole 12 feet in diameter right through to the bed of the Hudson River. It was impossible to get near the face. After trying many expedients, a thing like a plum-pudding in a canvas cover, 12 feet in diameter, was put into the hole by means of a large floating crane. The door was jacked open, and the material was allowed to leak slowly into the tunnel; and ultimately, by raising the air-pressure, it was

Mr. Moir. possible to get through the bulkhead, cut away the bottom of the plum-pudding, and build a chamber for the reception of the shield, which had come from Scotland. The erection of the shield began early in 1890, and by July, under a pressure of about 40 lbs. per square inch, it had been riveted up and put through the temporary bulkhead. There was very great trouble in erecting it in that position under so high an air-pressure. The chimney of the rivet-fire was nearly 2,000 feet long and 2 inches in diameter, and the draught was magnificent. On first commencing to push the shield there was great difficulty in keeping the tunnel from converting itself into a shaft. The ground was exceedingly soft, due to the eruptions of air to the river and other disturbances, and the sinking of the shield was very considerable. He received many kind letters from Sir Benjamin Baker at that time, encouraging him in his difficulties in trying to get the shield to run in anything like a horizontal direction, and those letters he had preserved and sometimes read for encouragement. Ultimately the shield was set going on true lines, but by the end of the following July it had stopped again, for financial reasons due to the Baring crisis in 1891. Between the time of starting and this stoppage, that was, in a little less than 1 year, 2,000 feet of tunnel were constructed; and he thought that, under the circumstances, this was very creditable, considering that those in charge were the first to struggle with the Hudson silt by means of a shield. When work was suspended, the jacks were filled with oil and everything was done to leave the work ready for whoever might come along to finish it; and he was glad that Mr. Jacobs had been able to use the same shield to complete the work. It was fortunate that the mud of the Hudson River had very little corrosive action, so that the steel plates were not much affected. When work ceased the tunnel was within 1,600 feet of the existing portion of the tunnel built by Haskin on the New York side. There were one or two other things of historical interest which were worth recording in the archives of The Institution. The men suffered severely from caisson-disease. In May, 1890, he introduced the first medical air-lock for treating caisson-disease by reimmersion, and that method proved a great success, curing, among others, his own chief, Sir Weetman Pearson, of paralysis, and also the President of the Ingersoll Rock-Drill Company. It was first used on the Hudson tunnel, and he believed the Author had used the same lock as one item of his plant: the method was now used on all important compressed-air undertakings and in the Royal Navy. He exhibited an interesting model of the lock presented to him by the men working in the East River tunnel contract, when

the 4 miles of tunnel for the Pennsylvania Railroad were finished. Mr. Moir. The model represented the locks used in the East River tunnels, where six of them were in operation. He regretted to say that in spite of every effort the chamber was occupied by a great many men for hours at a time, in order to relieve them from pain or bring them back to consciousness and life. Another historical thing of interest was the fact that a tunnelling-shield was first used in New York City, and also a hydraulic erector was there employed for the first time. Many Papers on shield-tunnelling had been presented to The Institution, and he believed there were no Proceedings in the world which contained so continuous and valuable a record of shield-driven tunnels as its Minutes; but there was one thing that never seemed to be touched upon in any of the Papers. The cast-iron lining of a tunnel of the kind under discussion accounted for at least one-third—and sometimes for an even larger portion—of the whole cost of the structure; yet nobody had yet made a scientific attempt to sovle the problem of the necessary thickness of the various parts of the castings: in fact, there seemed seldom to be any attempt made to find out what the bending-moments were in a tube. As the Author pointed out, a great deal of trouble was experienced with the early lining in the Hudson tunnel. The first 253 rings were too light; they were rough cast, that was, unplaned, and did not go together well; and the silt was so soft that the tunnel got out of shape and there was great trouble in keeping the lining from cracking. The lining cracked so much that on more than one occasion the men ran out of the tunnel and were with difficulty induced to go back. The engineer at that time was Mr. W. R. Hutton, who was loath to add to the cost of the tunnel and anxious to find out scientifically why the castings broke. By a series of calculations he made out that the tunnel-lining ought to break upwards, whereas it always broke downwards, and the cracks were longitudinal. Mr. Moir believed Mr. Hutton's theory was correct, but there was evidently some defect in its application. Seeing that the breakage occurred downwards, he tried to work out a graphical method to ascertain why the lining broke, treating the structure, as it was broken at the crown, as a pinned jointed arch. Knowing that the sides did not break, he drew out a link-polygon and a line of pressure in the arch and assumed that the sides were carrying all that they could to assist the roof. He was surprised to find that there was just sufficient load to break the tunnel-lining at the top. Indeed, so precise was the result, that he was sure there was something wrong! He therefore made a diagram and took it to Sir Benjamin Baker,

Mr. Moir. who characteristically remarked, "That diagram is all rot; you might as well assume the thickness of the iron as assume some of the data you have used in preparing it." Feeling much discouraged, he said, "Well, Sir Benjamin, I understand you, with others, were consulted as to what thickness should be adopted in the lining of the Blackwall tunnel; how did you arrive at the thickness of $1\frac{1}{2}$ inch under the land and 2 inches under the river?" Sir Benjamin replied, "We assumed the thickness, just as you assumed your data!" That showed what a master mind Sir Benjamin had; he did not need to depend upon theory, having a definite opinion as to what ought to be done and the courage to do it. Mr. Moir thought that had a bearing on the education of young engineers. There was no theory at present for the design of a cast-iron lining for a tunnel; but there were men who had had a practical as well as a scientific training, and who would stake their reputation on what they did. The Author had been trained originally among the class from which Mr. Moir himself had sprung, namely, mechanical engineers, and Mr. Moir was a strong advocate that all young engineers, should have a thorough practical training as well as a theoretical one at some technical college. Sir Benjamin Baker was strongly of this opinion also, having been in the engineering shops himself, and he possessed in a pre-eminent degree that experience and judgment which was vulgarly known as "rule of thumb." Mr. Moir was very glad to see that The Institution advocated practical workshop training as one of the most important features in its training scheme. In conclusion, he congratulated the Author on his admirable Paper.

Mr. Boycott. Mr. G. W. M. Boycott drew attention to the Author's remarks with regard to the precautions taken for the prevention of bends, namely, keeping the air-supply as pure as possible, and shortening the shifts. About 7 years ago, physiologists began to consider that the question of air-supply was of comparatively little importance, and at that time, being engaged on compressed-air work, he had an opportunity of making some observations, and was able to keep a daily record of the CO_2 in one large caisson and of a number of cases of bends, with the result that he could discover no connection between the CO_2 and the number of cases. At a later period he had the opportunity of repeating the experiment, but instead of taking the proportion of CO_2 he took the number of revolutions of the engine per man per shift, and obtained identically the same results. Therefore he thought that the precautions taken by the Author were inadequate. His own experience, covering shifts of $1\frac{1}{2}$ hour to 8 hours continuous and of 3 to 10 hours in the aggregate, had shown him that at less than 22 lbs. per square inch, it was

unnecessary to take any precautions, but that at a pressure of 24 lbs. severe but not fatal cases of bends might occur, and with a pressure of 28 lbs. fatal cases were very liable to occur. One of the two fatal cases he had known was the result of an exposure lasting considerably less than 8 hours. It was essential to remember that when such work was being carried on in years gone by, much less was known about caisson-disease than was known at present. Physiologists had since undertaken research-work of a very important character, the most important investigations having been made by Dr. Haldane in connection with the Admiralty Committee on Deep-Water Diving. He thought that up to a pressure of 35 lbs. per square inch with stage decompression the work might be carried on continuously for 6 hours quite safely. In a rock tunnel that was of great advantage, because the blasting and drilling and other operations could be carried on continuously by the same foreman and the same men for considerable periods; with short shifts the foremen and the men were not always certain as to what holes had been charged, and mistakes were liable to occur. He thought Dr. Haldane's researches were destined to revolutionize, even more than they had already done, not only the methods of working in compressed air, but also the conception of what was possible in that direction; and that in future 50 lbs. per square inch gauge-pressure would not be considered the limit of what was practicable—owing largely to the valuable work done by Dr. Haldane and his colleagues. Mr. Boycott.

Mr. H. H. Dalrymple-Hay remarked that the subject of the Paper was particularly interesting to engineers in London who had been connected with tunnelling work. One point that might appear small ought to be noticed. He believed the practice in America was almost invariably to let everything by contract, but in the case under discussion probably one of the most difficult pieces of tunnelling work ever executed had not been done by contract. As the Author stated, it was put out to tender, but the tenders were not at all satisfactory and the company took upon itself to ask its engineer to do it. The Author had been very courageous in undertaking the work, because it was impossible to conceive a more serious responsibility than having to advise people to embark upon an undertaking involving the expenditure of close on 12 millions sterling with simply no precedent as a guide: and he deserved the greatest credit. He believed the Author had constructed all the important tunnels under the Hudson, six in number, and they had all been constructed in quasi-fluid silt. The conditions were entirely different from what they were under the Mr. Dalrymple-Hay

Mr. Dalrymple-Hay. Thames. Under that river there were altogether about a dozen tunnels of various sizes—four or five in the London clay, others in the post-tertiary gravel overlying the London clay, some in the Woolwich and Reading beds and Thanet sands, and short lengths in chalk. Comparing tunnelling in any of the London materials with tunnelling in mud and silt as in New York, it was only right to say that what had been done in England in the last 20 years was of much less difficulty than what had been so boldly done in New York. While giving the Author credit for a great deal, it had to be remembered what a great work Sir Marc Isambard Brunel did without the appliances which had been at the disposal of the Author. Brunel made his shield about 37 feet 6 inches by 22 feet 3 inches, with twelve separate compartments each divided into three cells, or thirty-six working-cells, and was able to get across the river through ballast and silt with only candles to light him on his journey. Generally he had to keep a boat in the tunnel, and he was always in the tunnel himself. No doubt the Author had been in his tunnels a great deal, but probably he was much better dressed than Brunel used to be! Therefore he thought that the palm for tunnelling was still held by Great Britain. Taking the Blackwall, Greenwich, and Baker Street and Waterloo tunnels into account, he thought the work done by the Author was far better than anything that had been done in England. There were one or two points in the Paper which were of special interest to railway-engineers. The Author had used a minimum radius of about 150 feet (about $2\frac{1}{2}$ chains) for his curves, and on the section Mr. Hay noticed gradients of 1 in 25 and 1 in 27. Sixteen years ago, when he first started tunnelling, he was introduced to a 5-chain curve by the late Mr. J. H. Greathead, and Mr. Galbraith used to call them "right-angled" curves; but here the Author had used very sharp curves and very heavy gradients on a first-class piece of work. No doubt he would be able to give good reasons for what he had done. With regard to the strength of tunnels, Mr. Hay agreed entirely with Sir Benjamin Baker's view that it was just as useful to draw the section of a tunnel first as to try to calculate anything with regard to it. As an illustration, he might mention that the standard section for the lining of the tube railway tunnel between the stations (11 feet $8\frac{1}{4}$ inches in diameter) was arrived at in the rule-of-thumb way Sir Benjamin Baker advised. Miles of that section of tunnel-lining had been put into the ground, and in his opinion it was too strong, although he did not say that he would alter it. His reason for that view was that a good many footway-passages had been made round lift-shafts, where the ground had been weakened by the construction of the

shafts and the construction of openings between the shafts and the passages, and in making the openings between the shafts and the footway-passages the rings had to carry the weight thrown on them by a girder 10 feet long—about three rings' weight—which normally was about three times the load on the single rings of the running-tunnel between the stations. Therefore, nothing having gone wrong with them under three times the normal load, he thought it was fair to assume that they were over-strong in the running-tunnel. Some years ago he designed a tunnel-lining which was put in the ground not far from Westminster. It was of a very light section, and while it was being built some flanges of the lining broke under handling; but the tunnel was still standing, and afforded a certain measure of what would stand. It was well known that in constructing tunnels it was not only the load which the ground might bring upon the tunnel that had to be looked at; it was necessary to see also how the tunnel was to be made. If a great many piles were used in a tunnel constructed in the clay with a shield having many hydraulic rams, very bad cross strains might occur in the flanges, and thick flanges would be required to resist them. Again, when putting the segments into position the men used drifts in order to get the bolt-holes opposite one another; and as they drove the drifts in very hard the metal had to be strong enough to resist the stresses thus caused. Hence, it was not alone a question of what weight the ground would bring to bear: that nobody seemed to know, and he did not think it was possible to get at it. The best guide in the design of a tunnel was to see whether what had been done previously was anywhere near right. The Author had had occasion to fear that the strength of his tunnel might not be sufficient in the silt, and feeling that it was almost impossible to say whether the tunnel would sink or rise, he had taken the precaution of introducing longitudinal tension-members buried in concrete—that was, reinforced-concrete construction—in order to resist the sinking or rising effect by the introduction of a suspension-tie buried in the mass concrete of the tunnel. If the tunnel did move in that way there was a chance of the joints leaking; and if the joints leaked there was a prospect of some water getting into the reinforced concrete. In that event there might in time be rusting of the steel rods and consequent failure of the reinforced concrete, which would then be simply so much dead weight. There was nothing more interesting in the Paper than the pages which referred to the driving of the tunnel through the silt. As he understood the action, when in the silt the face was closed entirely and the shield Mr. Dalrymple-Hay.

Mr. Dalrymple-Hay. was pushed forward, forcing the silt on in front, and causing a regular flow of the material. That being so, the shield would tend to follow it and would move in an upward direction—in the line of least resistance. He presumed that the tunnel tried to do the same sort of thing, and that after a time it settled down. In driving forward with a tunnel alongside it was possible to conceive that the displacement caused by the large face of the shield moving forward would tend to distort or push to one side any tunnel already completed, and, of course, there was in that a little danger. If the Author contemplated driving any more tunnels under the Hudson River no doubt he would consider whether it would not be wise to try and keep tunnels as far apart as possible, in order to get over that difficulty.

Mr. Tabor. Mr. E. H. TABOR agreed that it was impossible to calculate exactly what a tunnel had to do in the ground, but he thought the Author would have a better chance of doing it in the Hudson silt than anyone had ever had before, because the material was so plastic that it might be possible with delicate pressure-gauges to measure the pressure at the top, bottom, and sides of the tunnel, through holes in the lining. In the ordinary way, however, it was quite impossible to say what the loads were. Mr. Moir had said that the old Hudson tunnel broke downwards, that was to say, it failed owing to the superincumbent weight, which was the most likely thing to happen to any tunnel in the ordinary way—or at any rate it was the tendency. According to Mr. Dalrymple-Hay, the only way to design tunnels was by judgment and rule of thumb. It was true that all the linings designed for tunnels had been arrived at in that way; but assuming that a tunnel failed by downward crushing, Mr. Tabor thought the strength of the lining of different tunnels might be compared by considering the tunnel-ring as a beam with flanges in tension. The lining was weak from that point of view, owing to the nature of cast iron. The bending-moment to which that beam would be subjected must increase with the square of the diameter of the tunnel. On that basis he had taken out the moment of resistance of the lining of different tunnels per lineal foot of tunnel, taking the channel section of the ring, and the square of the diameter of each tunnel in feet, and dividing the one by the other. The results of those calculations, which were only approximate, because he had not allowed for other details such as the design of the ring, having taken the rectangular section of flange, were rather remarkable. Considering that the tunnels had been designed by judgment and rule of thumb the results came out very close. In the case of Blackwall tunnel the square of the diameter of the tunnel in feet divided by

the moment of resistance of the cross section of the ring per foot— Mr. Tabor. sometimes known as the "Z" of the section—gave 12·8; in the Greenwich tunnel under the Thames it was 13·3; in the Rotherhithe tunnel 11·7; and in the Author's tunnel under the Hudson it was also exactly 11·7. In the Pennsylvania Railroad tunnels, it was 10·1 for the heavy lining and 12·8 for the light lining. Those figures were for subaqueous tunnels. Coming to the tunnels in London clay, for the ordinary section of tubes in London the figure was 19·4, which showed that these tunnels were considerably lighter. In the case of the station-tunnels of the same tubes the figure was 20·7. Considering that there had been no collaboration between the engineers who designed those tunnels, the results were in very close agreement. With reference to the down-town tunnel which passed through 2,300 feet of rock, he had tried from figures given by the Author to find out what the average progress per day through the rock was, but it was rather difficult, and perhaps the Author could supply that information. It must have been much less than in the silt. He also wished to know if compressed air had been used throughout in tunnelling through the rock, and if the rock was solid; because if so it seemed that a considerably lighter lining might have been used than was used in the silt. With regard to the minimum radius of 150 feet, by scaling from the plan, the curve of the railway entering Church Street station appeared to be only 90 feet in radius—a very sharp curve indeed. The Church Street terminus was an enormous piece of work and a very fine station, but the approaches seemed to be greatly inferior to the station itself. The approaches, which were sunk as caissons, cost £405,000, but the Author did not say what the cost of the station itself was. No doubt the matter had been well considered, but it would perhaps have been better if there had been two less-expensive stations, with the traffic divided between them, thus avoiding such costly approaches. With regard to the caissons on the New Jersey side—the crossover and Y-junction caissons—he thought everyone must admire the courage of the Author, who, when he found he could not get the structural steel in time, immediately changed the design to reinforced concrete, thereby saving a large sum of money and a good deal of time. The skin-friction in sinking the caissons appeared to be very high, and he would like to know whether the Author could give any explanation: was it due to the roughness of the surface, or to the caissons not being built quite as rectangular as steel structures would have been? Another example of the Author's boldness was afforded by the Church Street terminal station, where the

Mr. Tabor. original intention to construct the foundations for the columns carrying the building in the ordinary way was abandoned in favour of the compressed-air method when it was found that it would delay too much the construction of the 22-story building. That must have cost a very large sum of money, as there were more than a hundred columns.

Mr. Gravell. Mr. DAVID GRAVELL observed that it would be very interesting if the Author could give some details of the method it was proposed to adopt, or which perhaps had been adopted already, to support the Pennsylvania tunnels by piers 15 feet apart. With regard to advancing the tube through rock, he believed that no other instance of that had occurred, and he presumed that dynamite had been used for blasting. It would be interesting to know the maximum charges, and whether any repairs to the shield or apron had been required in consequence of the use of the explosive.

Mr. Hudleston. Mr. F. HUDLESTON thought that one of the most interesting points raised in the discussion was the question of the weight of iron to be used in tube tunnels. Mr. Tabor had given a good description of one way of arriving at the strength, but there was a simpler method, which he thought had guided both Mr. Greathead and Sir Benjamin Baker in their earlier practice. It was well known that in a cylinder the stress on the ring varied with the diameter for a given pressure, and the same thing occurred practically in a circular tunnel, assuming that the pressures were really radial. In the earlier tunnels, which were all based on Mr. Greathead's South London tunnel, the thickness of the skin was about $\frac{3}{4}$ inch. In the Central London, which was one of the earliest 11-foot $8\frac{1}{4}$-inch tunnels, the thickness was $\frac{7}{8}$ inch. All the other tunnels built in London clay had followed that example, varying in weight per lineal yard practically as the square of the diameter. That meant that the cross-sectional area of the lining varied with the diameter, and it would be found that that comparatively simple rule applied to the linings of all the London tubes driven in the clay. The tubes driven under the Thames were naturally heavier than those in the clay. The shield-chamber of the Bank crossover road on the Central London tunnel, which was 30 feet in diameter outside the skin, had a thickness of $1\frac{1}{2}$ inch. The thickness of the lining of the Blackwall tunnel was, he believed, 2 inches, $\frac{1}{2}$ inch more, and he fancied that the original designers had some such relation as that in mind. They made the lining of tunnels under the river distinctly thicker than that of land tunnels—in that particular case, about one-third thicker. The same ratio, he thought, would be found to hold good for all the tunnels, and he submitted that it was

a reasonable one. Mr. Tabor's way of comparing the sections was a little complex. Assuming the pressure was radial—and, after all, in tunnels under water it was very nearly so—the argument that the weight of iron should vary as the square of the diameter was sound. There were, of course, other practical considerations in connection with the tubes—for instance, the size of bolts. His own feeling always had been that the bolts in small tunnels should be just of such strength that a navvy could not twist them off. Everybody knew that in the hands of a navvy a $\frac{3}{4}$-inch bolt was a child, but a $\frac{7}{8}$-inch bolt was too much for him, and that was the smallest that should be used. At first sight it would appear that driving a tunnel through silt was a very novel piece of work, but it was not really very different from what had been done at Blackwall. When the shield got into the gravel at Blackwall they had to scrabble out the stuff at the back of the shield as well as they could; it was impossible to displace it in front as the Author had done, because it was far too hard. Practically the shield was driven by brute force through the gravel, and no excavation proper took place over a considerable distance. The shields that had been built for doing heavy work in the Rotherhithe and other tunnels under the Thames had all been designed with the intention that they should, if required, drive themselves through a full face of gravel; but the necessity for that did not arise in all of them. It arose at Blackwall, and at one or two of the smaller tunnels had been driven right through a face of loose gravel. In the Rotherhithe tunnel the roof was kept intact. Turning to the Paper itself, the Author spoke about the stability of tunnels in silt. It was an extraordinary thing that tunnels in such very soft material should not vary in level with the load that passed through them. He did not see anything in the description to suggest that there was any "breathing" of the tunnels when the trains passed through. He could understand that there might be what the Author spoke of, a rise and fall with the tides: possibly there was more compression of the silt at high water than at low water; but he did not see that it could be much more in this case, as he understood the range of tide at New York was small. It seemed to him that a rise and fall of the tunnel of $\frac{1}{4}$ inch was rather a great deal. He would like to know what happened when the trains ran through; was there any tendency for the tubes to "breathe"? If such a tendency existed, it seemed to introduce another complicated question, namely, the strength of the tunnel as a girder. The Baker Street and Waterloo tunnel ran in gravel for a short length, and the Blackwall tunnel for a length of 400 feet; and 400 feet of Mr. Hudleston.

Mr. Hudleston. tunnel, 27 feet in diameter, formed a fairly stiff girder: but it would be interesting to know something about the movement in a tunnel such as the Author's, running 2,000 or 3,000 feet through silt, and whether there was any tendency for the structure to undulate. It seemed to him if there was such a tendency it would be well to put in the props which the Author had proposed. When the work was in silt a slight motion would tend to create a slurry around the tube, which would make it too lively and always on the move. He had great admiration for the extraordinary work the Author had done, but he thought it should not be forgotten that such risks as the Author had taken were being put by engineers upon contractors every day.

Mr. Moir. Mr. E. W. Moir mentioned that in looking up some old notes he had found the original drawings of the shield he made under Sir Benjamin Baker's directions, and one or two proposals with Sir Benjamin's own pencil-marks on the drawings, and if they were of any interest to The Institution he would be glad to present them. He had been much interested in the remarks that had been made with regard to the strength of the iron lining. It seemed to him, however, that in the early days the fact that certain tunnels had remained standing with three rings of brickwork, capable of withstanding only 10 tons per square foot, might have had an important influence on the area of section adopted for the iron lining. Large sewers and other tunnels built with London stock bricks had provided very good data as to the loads carried. The bending-moment, however, in cast-iron tunnel-lining, which was a very important matter, had never been dealt with. Large water-pipes frequently split along the top. In the London clay the active applied force of the load on the outside of the iron was probably a great deal less than the passive resistance of the clay to the reaction of the tunnel-lining when it tended to spread and pressed against the clay. The clay formed a very firm abutment, and if the line of pressure tended to run outside the iron it had something to run into. But in the case of the tunnels under review, in soft silt, there was practically a fluid pressure without the capacity for passive resistance, and therefore the crown of the arch had to take up a bending-moment which in the case of a tunnel through clay would be taken up by the clay. In a rock tunnel the resistance of the material to such reactions was practically infinite; in London clay it was to all intents and purposes equal to anything that could be put upon it; but in the case under discussion, there was no such resistance.

The Chairman. The Chairman asked whether Mr. Moir could say anything about the London tunnels.

Mr. MOIR remarked that the Hudson tunnels in silt had been characterized as the most difficult ever constructed. He had had the honour and pleasure of working on the Blackwall tunnel in gravel and on the tunnel in the silt in New York, and therefore his opinion might be worth giving. The difficulties he met with in the first 2,000 feet of tunnelling in the silt at New York were nothing to what he had to face in going through the gravel under the Thames with only 10 feet of material between the tunnel and the river-bed. In New York, as the Author said, there was a watertight and air-tight material, and as long as the air was kept at a pressure equal to the hydrostatic head at the top of the tunnel, there was no danger to be feared, because the flow of the silt through the shield could be controlled. In the Blackwall tunnel, however, it was very different. As Mr. Hudleston had said, at Blackwall it was necessary to rake out the gravel through little holes 6 inches by 4 inches, and by brute force to push the shield, which would occasionally only go about 2 inches, after exploding several charges of dynamite in the gravel to shake it up. It was very difficult, even with twenty-seven 8-inch jacks and six additional 10-inch jacks placed around the bottom, the total pressure amounting in many cases to 5,000 tons, to get movement. Twice a day the face had to be got at through 3 or 4 feet of water. The wagons were drawn out with the spoil under water for hours at a time when the men were mining out at the top. No mining could be done at the lower levels at the bottom until the top had been finished and the whole face clayed over to prevent the escape of air, and frequently it was almost impossible to control the water. Therefore he was sure the Author, with his wide experience of sand and rock and silt, would agree that he would rather tunnel in the Hudson silt, bad as it was, than tunnel through broken rock or friable open gravel full of water under a river. Mr. Moir.

Mr. F. HUDLESTON thought that the conditions of a tunnel in silt were so nearly approximate to those of a tunnel in pure water, in which there was nearly a radial pressure all round, that the stresses in tunnels laid in silt were not quite so complex as those in a tunnel through other material. Mr. Hudleston.

Mr. H. RAYNAR WILSON wished to refer to two aspects of the Paper: the first, not an engineering question but closely allied thereto, was the economic aspect of tubes. Having taken much interest in the question of transit-facilities in large cities, he went to America about $3\frac{1}{2}$ years ago and investigated the conditions in New York, Boston, Philadelphia, and Chicago, and thus he was fairly well acquainted with the general scheme of the Hudson and Manhattan Railroad. He was also acquainted with the Pennsylvania Mr. Wilson.

Mr. Wilson. terminus and its tunnels under the Hudson and East rivers, with the enlargement of the Grand Central station, and with the great work that was being done, in the way of cut-offs, elimination of level crossings, and widenings, by the Long Island railway. All those large works had been carried out, as had the tubes in London, by private enterprise, and differed from the rapid-transit schemes of New York, Boston, Philadelphia, and Chicago, which were backed by the money of the municipality. It might be appropriate to quote some words spoken by Sir Robert Peel in 1844 on the occasion of the second reading of Mr. Gladstone's Bill for legalizing a scheme whereby British railways could be subsequently bought by the State. In these days, when private enterprise was so open to attack, Sir Robert Peel's words should be on record:

> "Without the advance of a single farthing of public money, what enormous advantages have been secured to the whole public by investment in this direction of private capital."

The other point he wished to make was the different way in which schemes were treated in America from what they were treated in Great Britain. That point had been fully gone into in the discussion of a Paper [1] by Mr. D. A. Matheson on "The Glasgow Central Station," when Sir John Wolfe Barry compared the practice in this country with the practice in Paris, and Mr. Elliott-Cooper and other gentlemen showed the difficulties that were put in the way of carrying out schemes in London. It really did seem as though every possible obstacle was placed in the way of carrying out schemes that were bound to be of the greatest possible benefit to the public and yet possibly might be of little benefit, and perhaps some loss, to the speculator. He found in the Report of the Royal Commission on London Traffic a memorandum by Mr. L. L. Macassey —to whom all interested in travelling-facilities in large cities were under a deep obligation—on the granting of the franchise for the Hudson and Manhattan Railway:

> "On the 28th May, 1903, an application was received from the Hudson-Manhattan Railway Company for a franchise to construct a tunnel from a point at or near the intersection of Broadway and Cortland Street in the Borough of Manhattan to the boundary line between the cities of New York and New Jersey, opposite a point between Liberty Street and Fulton Street in Manhattan. The Committee of the Board of Contracts investigated the matter and enquired into the finances of the applicant Company. The Rapid Transit Board granted a certificate much on the lines of those previously described, and transmitted the same to the Board of Aldermen with the customary acceptance of the franchise under the seal of the applicant Company. The latter approved the certificate on the 22nd December, 1903, and the Mayor on the 29th December of the same year."

[1] Minutes of Proceedings Inst. C.E., vol. clxxv, p. 30.

Mr. Wilson.

Another memorandum was given showing that the same expedition was observed in the case of the Pennsylvania Railroad extension. Application was made on the 5th May, 1902, and it was approved on the 23rd December following. It was hardly necessary to make any further comparisons or comment on that point. Another matter was the freedom that was enjoyed by engineers and contractors in the execution of works. Many members of The Institution would remember the chaos that prevailed around the Grand Central station, in Upper Broadway and in the down-town districts during the building of the Subway. Sir William White, in the discussion on Mr. Barclay Parsons's Paper on the New York Subway, mentioned that rock was blasted in the public streets with the greatest possible freedom, and similar things had been done in connection with the construction of the Pennsylvania terminal. He could not say that occurred on the Author's work around the Church Street terminus, but he knew there was a terrible noise, and the streets through which the carts passed with the excavated material were indescribable. In a book he had written on "The Safety of British Railways," he had expressed the opinion that the main cause of so many railway-accidents in America was the American's inherent love of taking chances, and the fact that he placed little value upon his own life or the lives of those in his care. That might be one reason, and it might be also that the alleged love of the American for the "almighty dollar" made him oblivious to other things. It might possibly be, however, that the municipal officials in America were more public-spirited. They had not to go before their constituents and justify their actions in the same way that councillors and members of city corporations had to do in England, and therefore they did not fear so much the result of their actions, and probably acted more impartially. At all events, those were things that required consideration. There might be, if things improved, a prospect of further facilities being given in London, but while matters remained as they were now, with restraint upon private enterprise, that was not likely to occur. With reference to signalling, it was on the New York Subway that he first saw the protection of trains by automatic signalling, and he had considered the signalling system there to be the best in the world. But as the trains on the District Railway were now worked with a headway of 1½ minute, and there was a similar headway on the Charing Cross, Euston and Hampstead Railway, the New York headway was no longer in the forefront. On the Hudson and Manhattan Railroad there was also a headway of 1½ minute, and he noticed in the Report of the Block-Signal and Train-

Mr. Wilson. Control Board that the trains were run at 50 miles per hour; but that he doubted. Although he had spent five of the best years of his life in preaching automatic signalling to apparently deaf ears, he did not consider that he had been connected with a forlorn hope, seeing that the success of the Hudson River railway, of the tube railways, and of the District and other electric railways was due entirely to automatic signals. The trains could not be worked with the rapidity with which they were worked, and therefore could not be so frequent, were it not for automatic signals; and as a signalling-engineer he prided himself upon that fact.

Mr. Ross. Mr. Alexander Ross, as one who had had something to do with tube tunnelling in London, had been struck with the magnitude of the work and the fortitude and confidence with which it had been carried out. The difficulties must have been enormous. As had been already said that evening, there had been very formidable difficulties in passing under the Thames with the Blackwall tunnel; the material, however, was of a more consistent character than a mixture of silt, gravel, and rock, and in the New York tunnels the difficulties had been greater. One thing that had struck him from a practical point of view was, that in the silt such a thing as grouting behind the lining was impossible; and he had in mind the question whether any deleterious consequences to the iron itself would result. Cast iron would withstand the attack of rust much longer and bear it much better than steel or other metals would, but whether it would stand for a long period under such conditions was a matter that might fairly be discussed. He had also been struck with the vast and expensive character of the work and the reduction in its value caused by the introduction of very sharp curves: such a course seemed to him almost to endanger the full benefit to be got from the work. He thought a strong effort should have been made to increase the radius of the curves, as they must, to a large extent, detract from the effective use of the railway, and would, like an excessive gradient, reduce the hauling-power of the line. Mr. Galbraith had had much experience of a tunnel passing under the Thames where there was a curve of 5 chains radius, and Mr. Ross knew he regretted very much that he had been unable to get a longer radius. He joined with previous speakers in congratulating the Author. He was pleased that Mr. Barclay Parsons had come over and given a very graphic and valuable description of the Subway in the City of New York, and that Mr. Jacobs had now come and described the work under the rivers; and he hoped that another engineer would come

later on and describe the tunnels under the East River, and in that way let London know as much about New York as New York knew about London. Mr. Ross.

Mr. W. J. E. Binnie congratulated the Author on the design shown in Figs. 12, Plate 3, the station with the island platform. At each station of the Central London Railway there were two tubes 21 feet $2\frac{1}{4}$ inches in internal diameter, with a platform and line of rails in each. The 21-foot $2\frac{1}{4}$-inch station-tubes cost three times as much as the 11-foot $8\frac{1}{4}$-inch running-tubes. In Figs. 12 there were two ordinary tubes with the intermediate piece broken out. Mr. Binnie.

The Author, in reply, observed that no words could sufficiently express his thanks for the cordial reception of his Paper or the pleasure he felt at having been fortunate enough to deal with a subject so interesting to the members of The Institution. Mr. Moir had suggested that something should have been said about the past history of the work. As a matter of fact, he had written a number of pages about the past history, as well as a good deal about the setting out and the instrumental part of the work; also with reference to signalling and ventilation: but on reading it over he had found he was writing a book and not a Paper, and therefore he had withdrawn it. He had been pleased to hear Mr. Moir's description of the early work: a large amount of credit was due to the early pioneers. Mr. Moir had referred to the accident that occurred to the late Sir Benjamin Baker, who was caught in the lock. Mr. Jacobs had always considered there was a danger of not being able to close the inner door in order to lock out, and one of his first "lifeboats" was a small lock-extension about 4 feet in diameter and 4 feet long, the open end of which was provided with a flange which would fit on to the outside of any of the locks, and the other end with an ordinary lock-door. A man was caught when the lifeboat was on the New York side, but it was taken across by the ferry to the Jersey shaft, and bolted on to the end of the lock, the air-pipe was connected up with it, and the pressure was equalized at once and the man thus set at liberty. He believed that in all compressed-air work a safeguard of that kind was almost essential to the safety of the men working inside when inability to equalize the pressure, through the jamming of a door or some accident to one, might lead to fatal results or the loss of the heading. With regard to working under air-pressure, he had had considerable experience and was sure that at high pressures the percentage of CO_2 should be kept as low as possible; also that, in general, the analysis of the air should always be subject to the approval of a first-class medical man. The The Author.

The Author. physical condition of the men should be carefully looked after, and any troubles occurring to a man should be reported immediately to the medical officer and the man suspended from further work. The men had to be nursed more like children than intelligent men. With regard to air-pressure at 50 lbs. per square inch, the first tunnel he built in New York was under the East River, in 1893, and the pressure there for a considerable time ranged from 48 to 51 lbs. and a $1\frac{1}{4}$-hour shift was considered the safe limit. He thought that the time during which men worked in a shift had a very important relation to the pressure, and the physical condition of the men and their careful watching had much to do with their safety. The medical lock had proved to be indispensable. The next question raised by several speakers was the 150-foot curve in the tunnel. All the lines were subject to a franchise, and the franchise granted indicated precisely how the tunnels were to proceed. The only way was to take them through the streets. The land-values of New York were enormous, and it would be impossible for any corporation, except a municipality, to carry tunnels under property. Therefore the 150-foot curve had had to go round Morton and Christopher Streets. The route was at the mercy of the franchise and of capital, and there was no other means of bringing the tunnels in, except by the 150-foot curves. Fortunately the curves were close to stations, and therefore there was no question of speed in running the trains round the curves. With regard to the pressure on the tunnels, there were gauges indicating very clearly the pressure around the tunnels in the Hudson River silt, and, as had been suggested, it was very nearly equal all round. Elaborate calculations had been made in relation to the strains on the linings. As to the average speed through rock, endeavour had been made to get in as nearly as possible one ring per shift. The rings were 2 feet in width, and the average aimed at was 6 feet per day in rock formation, and very nearly 5 feet was accomplished. With regard to the Church Street terminus, there had been no alternative but to bring the tunnels in at right angles to the station, and therefore sharp radii were unavoidable. The fact of lines being built in concrete caissons afforded readier means of arranging the necessary clearance. With regard to the skin-friction of the caisson, the ground was water-charged and of a freely-flowing nature, thus exerting considerable pressure against the structures, which he considered were built as true as it was possible to build concrete structures of such a size. He did not agree with the speaker who considered that the friction was much in excess of what might have been expected under the

The Author.

circumstances. A very able description of the Pennsylvania tunnels with the columns would be found in a Paper which was under discussion by the American Society of Civil Engineers. In blasting the rock eight holes were generally used, and in the streets about 8-oz. sticks of dynamite; in the river sometimes twelve holes were drilled. The shield became damaged and the aprons were also injured, and the structures themselves often required repairs. As to the simplicity of tunnelling through silt, he admitted with Mr. Moir that it was not a very difficult question now that it was thoroughly understood, but the difficulty of blasting the rock under the North river with about 10 or 12 feet of silt above the heading and 60 feet of water was another matter. That work had required considerable courage and determination, and sometimes the men had been driven almost to the limits of physical endurance. He knew of no more dangerous work than blasting rock with a head of water above such soft silt as existed near the water. Another great difficulty about the work had been to carry tunnels through beds of sand under the streets, with elevated railways and huge buildings above them in every direction. It was a point in the work for which credit should be given, because it was a unique achievement to tunnel through rock, sand, and gravel under streets, with such superimposed weights that must not be disturbed in any way.

Correspondence.

Mr. Barlow.

Mr. Crawford Barlow felt that the very interesting description of the numerous works in connection with the Hudson River tunnels was, on account of the quantity of matter to be dealt with, rather of a skeleton-like character, and some interesting details were omitted. For instance, there was no account of the early history of these tunnels: more than 20 years seemed to have elapsed between the beginning of the first tunnel and the time when the Author was called in, and it was known that the assistance of the late Sir Benjamin Baker was obtained at one time. It would make a more complete record if some slight sketch were given of the history of these past struggles for the mastery of the Hudson River. The greatest novelty in the constructional work was the hardening of the clay in the river-bed by burning kerosene. It would be valuable to know the arrangements made for carrying off the gases from the burnt oil and keeping the tunnels habitable for the men during the process. Again, in reference to the scheme for carrying the live

Mr. Barlow. loads independently of the tunnel-lining, although this had not been carried out, certain queries suggested themselves, namely, the sizes of the piles or piers, the method of carrying them through the bottom of the tunnel so as to keep out the water and sand, and the character of the girders for carrying the rails from pier to pier, considering the limited area of the tunnel. This scheme was another exemplification of a modern branch of engineering, which might be said to have been initiated when the Tower subway was constructed. Brunel's patent of 1818 had defined a circular shield, but neither at the Thames Tunnel nor in any of his works had he employed his patented arrangement. When the Tower subway was opened for traffic it was described as a model of a system of tunnelling especially applicable for driving under the streets of cities or under rivers, and Mr. Peter Barlow in the following year obtained an Act for the first sub-metropolitan scheme on this system, namely, the City and Southwark subway. Unfortunately, financiers had not then realized its future value, and the scheme was abandoned. On Mr. Barlow's retirement from business, on account of ill-health and age, the scheme was handed to Mr. Greathead, who revived it in 1884, and eventually extended it to south London, hence its present name, City and South London Railway. There was a fact connected with the Tower subway which he believed had not been made generally known. When the Tower bridge was completed the subway lost the little traffic it possessed and was for sale. The Hydraulic Power Company made an offer for it (for laying their mains from south to north London) subject to the iron lining being found to be in good order, that was, not corroded away, as had been predicted by many people. Holes were cut through the iron to the clay, and in every case the cast iron was found to be as good as when first put in, the cement ring on the outside and the tarring on the inside having kept it in perfect preservation—a fact which was reassuring to those who were concerned with the future of these iron tunnels.

Mr. Berridge. Mr. Harold Berridge, having been connected with the work for about 7 months, could bear testimony to the skill, energy, and foresight with which it had been conducted. With regard to the design of such subaqueous cast-iron tunnel-linings, he had found that by plotting the weight per foot (W) against the product of the hydraulic depth, H, and the external radius of the tunnel (R), that

For heavy tunnels $W = 11 \cdot 9 \times H \times R$
For ordinary ,, $W = 9 \cdot 5 \times H \times R$

The latter seemed to be a minimum weight, as the old Hudson

tunnel-lining, which failed, came below this figure, as did also a Rapid-Transit tunnel between the Battery and Joralemon Street (Brooklyn) which had also given trouble. The higher weight-factor coincided with such linings as the St. Clair and the heavy Blackwall section. There was of course a desire to cut down the weight of linings, owing to their cost forming such a large portion of the total; but in gravel and ballast the stresses set up in the lining by pushing the shield ahead were very severe and concentrated, and, especially in smaller tunnels, were apt to cause longitudinal fractures if the lining was not strong enough. There seemed to be little information generally available as to the quantity of compressed air necessary for tunnel work. The supply for several tunnels appeared to be about 15 to 20 cubic feet of free air per minute per square foot of face. Perhaps the Author could state on what basis the air-compressor plant had been laid down for work in gravel and silt respectively. The Hudson silt was fairly good for plastering crevices, and he had a vivid recollection of spending a whole Christmas Day, when hands were short, in finding air-leaks in the face by the light of a candle and plastering them up from a bucket of Hudson silt, with the object of keeping the compressor-revolutions down to a reasonable figure. The silt, however, dried very quickly when so used; so that, on that occasion at any rate, he had put in a full day's work, the temperature at the face being 90°, and on the top −4°, which afforded an example of the local conditions sometimes occurring. The use of reinforced concrete for caissons appeared to be eminently successful and showed that the material could be trusted to develop the required strength for this class of work within the comparatively short time necessary. Mr. Berridge.

Mr. A. FAIRLIE BRUCE observed that some information regarding the setting-out of the lines of tunnel, which must have been somewhat troublesome, would be of interest. He considered that the Author had shown great wisdom in making such free use of reinforced concrete, on account not only of its economy in construction, but also of its freedom from risk of corrosion, to which all ironwork was liable in confined positions difficult of access for painting. Mr. Bruce would be glad to learn the result of the Author's experience of the twisted rods used for reinforcement. Judging from his own experience, he was not inclined to attribute any great virtue to patented forms of reinforcement, which were open to the objection that where they overlapped at junctions they would not lie so close together as plain rods, whether round or square: this was a serious consideration in thin work, or in places where two or more systems of reinforcement Mr. Bruce.

Mr. Bruce. intersected. The Author might also be kind enough to state whether in making the connections between different lengths of rod, especially in the columns, he merely overlapped and wired them together, or adopted some special method. It would also be of interest to know how the plugs in the caissons were arranged for connections with the tunnels, and whether they were of plain concrete or were reinforced; also whether the reinforcement had to be cut through for their removal. Lastly, when Caisson No. 3 was stopped on reaching the rock, was it supported merely by skin-friction while the rock was removed and the walls were built up from below?

Mr. Deane. Mr. HENRY DEANE, having sat recently on a Royal Commission dealing with the question of communication between North and South Sydney, was glad to see that some of the difficult problems likely to be encountered if the tunnel scheme recommended were adopted had been dealt with successfully by the Author. At the present time communication between the two shores of Port Jackson was entirely by private ferry, and as the Author referred to the way in which the ferry-traffic across the Hudson had been conducted, it might be mentioned that Mr. Deane, during his term of office as Engineer-in-Chief under the Government of New South Wales, had recommended on more than one occasion the introduction of the American practice of double decks and end loading, in order to facilitate the movements of passengers when embarking and disembarking. Port Jackson was much narrower than the Hudson River at New York, but it resembled that waterway in that it was frequented by large ocean-going vessels. The desirability of keeping the fairway clear of the obstruction caused by bridge-piers and superstructure was strongly insisted upon by some of the Sydney authorities on navigation. The tunnel method of communication was at any rate cheaper to start with, as it consisted of comparatively small units; a tunnel did not require to be in an absolutely straight line, but could be curved in order that the best ground might be selected, and it could be extended up and down the stream, and also added to as required, by the construction of additional tunnels. The conditions met with in carrying out the Hudson River tunnels had been dealt with very successfully. They appeared to have been almost unique as to variety. Soft silt, fine running sand, boulders, made ground, and rock, had offered no impediment to the Author's operations, although rock had frequently occurred at the bottom of the tunnel sections only. It was reassuring to the engineers who would have to deal with the Sydney case to note that the Author had pushed his tunnels through material which was much softer and more treacherous

than they were likely to find at the bottom of Sydney Harbour. He was glad to observe that the Author condemned the crossing of opposing traffic at junctions on the level as dangerous, and avoided this by taking the lines in single tunnels and passing one over the other. He had already resorted to that principle in a proposal worked out by him for the Minister for Works some years ago, and also later on in dealing with the junction of the eastern suburban line with the city railway scheme, which was at the time under consideration by the Minister then in office. He considered that by adopting this method not only would the danger of opposing traffic crossing on a level in the tunnel be avoided, but also the number of trains that could be passed through the junction would be very largely increased, as the traffic in one direction would not have to wait for the passing of that in the other. The Author's arrangement of the lifts, whereby entrances and exits were provided on opposite sides, was much to be commended. One of the most important sections of the Paper was that under the heading "Stability of Tunnels in Silt." It was certain that most engineers would have hesitated to trust such material, and the experience recorded was therefore very valuable. The Paper was full of details which, on account of their variety and novelty, would be of the greatest service to engineers. Mr. Deane.

Mr. E. P. Goodrich, of New York, remarked that the subject of tunnel-building had made great strides in the United States in the last few years, and unquestionably the tunnels described in the Paper were examples of the highest development yet reached. This was true because of the adverse conditions encountered and surmounted as well as on account of the application of such miscellaneous devices as reinforced-concrete caissons, the baking of clay to be excavated, tunnel-construction by displacement, etc. His own special interest centered perhaps more particularly on the earth-conditions encountered, and on the reinforced-concrete work. The pressures developed in the jacks which projected the shields forward, when analysed on the basis of the lateral earth-pressures produced, in terms of the vertical weight above any given level, served as a basis for computing coefficients which might be used under similar conditions for the determination of lateral earth-pressures in retaining-walls, foundations, etc. Again, the information given with regard to the movements of the tunnel due to tidal changes and occurring in the course of time proved conclusively that soils possessed the property of resiliency or elasticity. This point had been brought to the attention of the American Railway Engineering and Maintenance of Way Association in a Paper by Mr. Goodrich at its last Mr. Goodrich.

Mr. Goodrich. annual convention, and the Author's notes were particularly interesting in this connection. With regard to the subject of reinforced concrete, he was surprised that a higher ratio was allowed between the moduli of elasticity of steel and concrete in compression than in so-called tension, which latter he understood to be the tension developed by bending. The majority of experiments with which he was familiar showed that in direct compression the ratio was usually in the vicinity of 10, rarely rising above 12; while in the case of bending it was rarely below 15, and often rose to 18 or 20. The various applications of reinforced concrete, such as those in the caissons and the stations, were of considerable interest and illustrated strikingly the possible uses of the material.

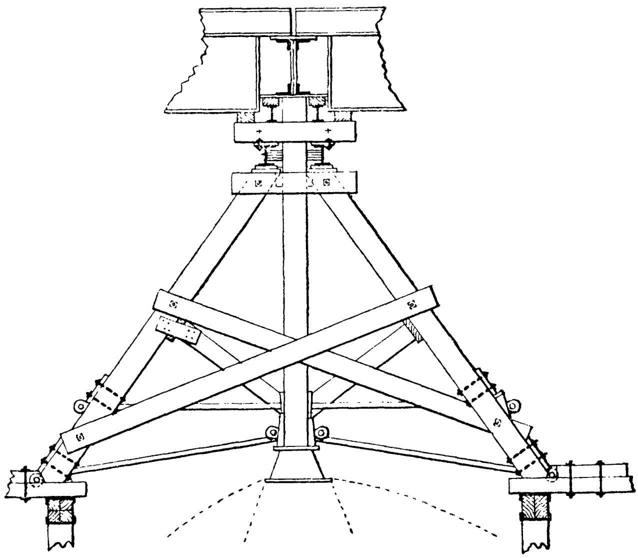
Mr. Leitch. Mr. W. O. Leitch observed that the completion of the old Hudson River tunnel was an event of historic interest. The original promoter was the first to use compressed air for tunnelling, and the pilot-tunnel supporting a lining of thin plating, inside which the brickwork was built, was also first adopted there. The past history of the tunnel obviously could not be included in the present Paper, but it was to be hoped that the Author would cause to be prepared a memoir which might well be called "The Romance of the Hudson Tunnel." Two striking facts were the magnitude of the work and the large portion done under the direction of the engineer. Large undertakings had been frequently carried out by executive engineers in India and China, but in countries where occidental customs prevailed the contract method was more common. For a speculative work such as tunnelling under the Hudson, and under valuable property, a contractor must allow for risk as well as profit. If the risk did not arise, presumably the railway-company gained by undertaking the work itself, but, on the other hand, contractors accustomed to such work might be able to work more economically. Consequently the cost was a matter of much interest. The 12½ miles of single tunnel were stated to have cost £6,000,000, which worked out at £91 per lineal foot. The cost of the concrete arched tunnels would be below the average, and that of the iron-lined tunnels above, so that the cost given for subaqueous iron-lined tunnels—£60 per lineal foot—appeared to require some further explanation. Did the £60 include engineering, management, plant, and all general and operating expenses? The same question might be asked in connection with the price per cubic yard for excavation. It would be interesting if the Author could say something about the 500 feet of 19-foot tunnel that failed. Were the joints all machined? With such peculiar material as the Hudson silt, excavating might have caused move-

ments in the surrounding material, bringing unequal pressure on the tunnel. The 16-foot ring was of thicker plating, and ramming the shield into the silt probably consolidated the latter. Were there any records to show whether the old shield used by Messrs. Pearson had sunk during the time work was suspended? Also, had any of the tunnels been built with the segments breaking joint? With regard to air-locks, could the Author state the pattern found to be best from the point of view of rapid working, including bulkhead- and caisson-locks, as well as small locks where the man- and material-locks were in one? The description of the run of silt through a door of the shield helped one to realize the difficulties of the early days. The shields apparently had a single diaphragm, and if so it was rather doubtful if the saving in cost and the greater ease in manipulating a lighter shield balanced the risk of a run of silt. The placing of the canvas sheet so as to block the mouth of the tunnel was a very ingenious operation, and it might be worth while recalling that Trevithick tried it under the Thames almost exactly 100 years ago. During the last 15 years many bridge-caissons had been sunk by compressed air in North China. No very high pressures had been required, but up to 30 lbs. per square inch the Chinese workmen had stood it very well, and had proved apt at the work. There were at present a few sub-contractors, trained by the engineers of the Imperial Railways of North China, able to undertake the running of the machinery and the sinking at remarkable rates. Thus bridge-caissons recently sunk through sand and silt and founded on rock 30 to 55 feet below water-level, had cost on the average 2*s*. 6*d*. per cubic yard for excavation. Plant and coal, etc., were supplied free. Other expenses counterbalanced the cheap labour; cement and steel were expensive, and, for example, in the case of the Lanchow bridge (Kansu), all plant and workmen had had to be sent 1,100 miles over rough roads. Mr. Leitch.

Mr. J. C. Meem, of New York, remarked that under the guiding hand of the Author and his able assistants there had been evolved a practically new idea in tunnelling, which had rendered apparently simple that which at one time was almost prohibitive: he referred to the method of driving a shield through the Hudson River silt without taking in any, or at least only a small portion, of the displaced material. He had been studying for some time the effects of skin-friction on piles and caissons, and he was convinced that friction was largely an element of pressure, and that between similar faces it would always be constant at the same pressure; owing to the arching tendency of ground over small areas, such as the space occupied by piles, it would therefore be materially Mr. Meem.

Mr. Meem less on piles than on large caissons. While he was not able to analyse the Author's notes on the skin-friction of the large caissons, with respect to this particular theory, he believed that such records were always of great value, even though they might not differentiate between skin-friction pure and simple and that due to binding, which was in reality of bearing value. Referring to the Author's description of the underpinning of the elevated railway in Sixth Avenue, New York, the following description of similar work in Brooklyn might be of interest. The Brooklyn extension of the New

Fig. 21.



York Rapid Transit Railroad, as finally built, comprised four tracks along Fulton Street and six tracks along Flatbush Avenue, some of which were depressed. Along Fulton Street, for a distance of 2,700 feet and along Flatbush Avenue for a distance of 2,000 feet, the route lay under double-track elevated railways, the columns of which had to be underpinned in order that they might be seated on the roof of the structure. In Fulton Street the columns were of the Phœnix type, carrying cross lattice-girders, which in turn carried longitudinal girders supporting the track, the columns being seated just inside the curb. Along Flatbush Avenue the columns were seated

in the roadway, just outside the surface tracks, and were of the channel-lattice type with flared heads, carrying cross plate-girders, which in turn carried longitudinal girders. The two types of structure thus presented very different problems. Omitting mention of the special cases where turn-outs of the surface tracks introduced complications, the following was a description of the method of underpinning adopted in typical cases for each type of structure. Box-sheeted pits 5 feet square were first sunk about 10 feet each way longitudinally from the columns to or slightly below the formation-level of the adjacent structure. On floor-grillage in these pits 12-inch by 12-inch posts were set, and from longitudinal caps on these, double A frames of 10-inch by 12-inch yellow-pine timber were set up, on the tops of which a grillage of I beams and timber bore against the columns and structure as shown in *Fig. 21.* Eye-bars with 3-inch pins were then placed, the pins bearing on 4-inch by 4-inch wrought-iron bars, bolted to the legs of the A frame as shown. The bars were tightened as much as possible by hand, and then hydraulic jacks were set on the pins on one side, and they were pressed down till the column showed signs of being lifted from its base. The pins were then made tight and a secondary set of eye-bars was placed and tightened down, and such other bracing and protection as might be required was inserted. As the ground above the footing of the columns was excavated in the course of the regular work, the masonry base was dropped and blasted so that it could be removed, and the column was left on a temporary footing till the permanent structure was erected underneath. The uprights, etc., were incorporated in the general scheme of bracing as the work advanced. The Phœnix columns along Fulton Street were supported by a collar which was bolted to the column, being supported by the outside legs of the A frame, above which the head of the column was blocked up. The inside legs, abutting each other and carrying cross caps, were blocked up under the main cross girder. Side rakers of 10-inch by 12-inch timber were used to prevent lateral swaying. Bearing-channels were used between the heads of posts or steel beams and flat timbers where necessary, to distribute the load. In most cases there was some settlement of $\frac{1}{4}$ inch to 2 inches, and when the column was ready to be set on its new base the bars were tightened and jacked down until the column was back to its original elevation plus $\frac{1}{4}$ inch. The 2 to 3 inches of space between the bottom of the column and the top of its base was then wedged up with steel shims and grouted, being allowed to set for several days before the bracing was removed. At one time the exigencies of the work were such that seventy-six columns along Mr. Meem.

Mr. Meem. both Avenues were off their permanent footings. At Flatbush Avenue and Fulton Street there existed five tiers of standard tracks, including two elevated railroad lines crossing each other, standard surface lines, a five-track subway and one standard subway. Mr. Meem was indebted to Mr. F. L. Cranford, of the firm who carried out this work, for his courtesy in allowing these particulars to be given, he himself being engineer for the firm.

Mr. Taylor. Mr. C. P. TAYLOR noticed that in describing the novel arrangements made for driving the tunnel partly in rock and partly in silt, the Author referred to a steel apron for the overhead protection of the men while drilling, and as a safeguard against the inflow of silt. Later on he referred to a removable protecting hood used for the same purpose, and serving as a poling-board in soft ground. Presumably the silt met with just above the rock was as soft as that through which the tunnel had been driven either without removing any material at all or by allowing only a small percentage to flow into the heading through the shield. Under these circumstances it would appear that something more than overhead protection had been required during the process of drilling the rock. It would be interesting if the Author could give a diagram showing exactly how the space necessary for the drilling-operations had been secured.

Dr. Zollinger. Dr. A. ZOLLINGER, of Berne, remarked that such works as the tunnels between New York and New Jersey would be carried out only in large cities where the traffic had become so dense that ordinary methods of communication failed. Intercommunication by means of large bridges had the disadvantage of being very costly, for on account of their height above the banks of navigable rivers and their great length, as well as the space taken up by approaches, it was not possible to obtain such direct communication with the centres of traffic as was to be desired. Hence recourse was had to tunnels, which could be constructed more easily without interfering with traffic, and, especially, which could be connected with busy centres as needed. The difficulties with tunnels were the sewers and mains under the streets; but in course of time subways would be constructed to carry these, which would greatly facilitate the proper maintenance of the streets and prevent them from being obstructed so often. The greater part of the work had been carried out under compressed air; with that system there was a limit to the depth, because it was not possible to exceed a gauge-pressure of 45 lbs. per square inch, or a depth of about 100 feet below high water. If this depth were exceeded it was necessary to employ freezing methods, which required very uniform ground and large installations, but which usually enabled excavation and

Dr. Zollinger.

masonry work to proceed very quickly. The longitudinal profiles indicated that the rock had been avoided as much as possible in tunnelling through the silt. Would it not have been better to remain more in the rock? because construction was less costly than maintenance. Probably enough soundings had not been made to determine exactly the profile of the rock, which in the case of the down-town tunnel (Fig. 4, Plate 2) was very irregular; but why had the tunnel not been kept at the same depth between Caisson No. 2 and the crossing of the Hudson, in which case it would have remained in rock all the way on the right bank of the river? A gradient of 1 in 25 should have been avoided for a line with heavy traffic, on account of the great fluctuations in the current. Concrete offered great advantages over masonry, being executed very rapidly, but it was necessary to employ skilled workers, and the concreting must be done carefully. In the Lötschberg tunnel, $8\frac{3}{4}$ miles long, through the Alps, blocks of concrete were used. Two plants had been laid down for making these blocks, and the concrete, which was made with Portland cement and crushed-stone sand, had a resistance to crushing of 2,550 lbs. per square inch after 28 days. Three qualities of matrix were used, having resistances to tension, after 28 days, of 230 lbs., 142 lbs., and 114 lbs. per square inch respectively. These were used according to the resistance required in the different kinds of work. The use of cast iron for tunnels subjected to bending action was not to be recommended, for usually the excavation was never made so exactly that the tube rested everywhere on the ground; the only advantage of cast iron was that it resisted chemical action better. But steel tubes could very well be employed if surrounded with a sufficient thickness of concrete; steel resisted movements better owing to its elasticity. The permanent way consisted of rails resting on wooden cross sleepers, the whole supported on ballast, as was usual in America. In London special rails were used resting on longitudinal sleepers, and the bed was of concrete. Dr. Zollinger preferred the latter form in a long single-line tunnel; the construction cost more, but the upkeep less. In the former there were less fastenings and the changing of the ballast was avoided—work which was very costly in a single-line tunnel where there was not much room or time for adjusting the track. With a concreted bed the drainage was always maintained and the track lasted longer. The workmen's wages were high, but the work was done by skilled men, from whom more could be expected. The continuous-current third-rail system was always appropriate where the traffic consisted of a large number of light trains. In the Simplon tunnel electric traction by three-phase

Dr. Zollinger. current at a pressure of 3,000 volts had been employed from the beginning. Electricity had been chosen because of the great heat in the tunnel. The traffic consisted of about twenty-six trains in the two directions every 24 hours, their speeds being 42 and 21 miles per hour. The tunnel was continuously ventilated with 1,765 cubic feet of fresh air per second (the cross section being 250 square feet) and the maximum gradient was 1 in 143. In spite of these favourable conditions it had been found that in the damp parts of the tunnel an extraordinary amount of wear occurred on the tops of the rails—which weighed 108 lbs. per yard—there being places where the wear had amounted to nearly $\frac{1}{4}$ inch after 3 years' working. Such wear had not been found in a similar long tunnel, also very damp, and having a gradient of 1 in 37, through which seventy to eighty steam-trains passed per day. The wear in the Simplon tunnel had been attributed to electric traction, but the actual causes had not yet been discovered.

The Author. The AUTHOR, in reply, remarked that no special arrangements had been made for carrying off the gases when hardening the clay in the face by burning kerosene. A large quantity of air was escaping at the time, which helped to remove the gases, but this was one of those emergency measures so common in engineering which had to be carried out in spite of conditions involving considerable discomfort, and in fact some danger and risk to the workmen. Regarding the size of the piles or piers which were designed for the Pennsylvania tunnels to carry the live load independent of the tunnel-lining, it would of course be understood that while within these tunnels segments with cast-steel bores in the inverts of the tunnels had been installed, permitting the introduction of piles without exposure of the ground, the piles had been omitted after a full investigation of the stability of the tunnels. For the information of Mr. Barlow, however, it might be stated that the keeping out of the water between the tunnel-lining and the piles was to have been accomplished by means of an ordinary stuffing-box, in some respects similar to the stuffing-box of a steam-engine, except that the packing was intended to be metallic and so arranged that the gland could be kept tight. As the piles were to be placed 15 feet apart between centres, the longitudinal girders to carry the track were themselves carried on transverse bolsters, or girders, resting on the top of each pile and were necessarily quite shallow. The piles were to be $29\frac{1}{4}$ inches in diameter. This matter was being fully dealt with in the Papers at present under discussion by the American Society of Civil Engineers, treating on the construction of the works involved in extending the Pennsylvania Railroad into

New York City by means of tunnels under the Hudson River, to which the Author had already referred. In response to Mr. Berridge's inquiry as to the basis of compressed-air supply, as explained in the beginning of the Paper, the work had not been planned as a whole at the start, but the system as built had been developed and enlarged from the original tunnel after several years of study, during which time work had been in progress on portions of the undertaking. It had therefore been neither necessary nor desirable to lay down a compressor-plant of sufficient size to carry on all the work at once. The compressors used on the tunnels which were completed first had been transferred to new locations and used on the later tunnels, or else the air had been piped, either through the completed tunnels or on the surface over the uncompleted land tunnels, to new points of attack. An accurate forecast of the quantity of compressed air required under all conditions could not be made. The Author had had a single face using 20,000 cubic feet of free air per minute in gravel, and also in silt when the bed of the river was torn; while, on the other hand, one-fifth of that quantity had sufficed under normal conditions. As each of the five principal plants on this work had supplied air to two to four or more faces, the chances were that these abnormal conditions would not prevail at all faces at once. At any rate, the ability to concentrate the supply of air on one face, temporarily ceasing work on the others, had given a great reserve of air for emergencies. In reply to Mr. Bruce, steel reinforcing-rods were overlapped at points where rods in one continuous length could not be used. Twisted steel rods were used throughout, no patented form being used. The plugs in the caissons were made by first putting in the ends a ring of the 19-foot $5\frac{1}{4}$-inch tunnel-lining left over from the old original tunnel, inside which a plug of plain concrete was made; this was cut out when a shield was driven through the tunnel-lining, telescoping inside the larger ring, and the small annular space was filled with concrete. In regard to the support of caisson No. 3 while the rock was being removed and the invert and walls were being built, it was held in position partly by the skin-friction, partly by the bearing of the cutting edge on the rock, and partly by the air-pressure; but as an additional precaution wooden blocks and props were used, the points of the support being shifted as the excavations progressed. In regard to the ratio between the moduli of elasticity of concrete and steel, Mr. Goodrich had been misled by a misprint in the proof of the Paper. The ratio $\frac{1}{12}$ to $\frac{1}{15}$ related to beams, and the lower ratio had been used as a rule, as that conformed to the requirements of the New York building laws, the higher ratio having been used in only a few The Author.

The Author. cases where the necessities required it and the building laws did not govern. The ratio of $\frac{1}{15}$ to $\frac{1}{20}$ related to columns, and also in this case the lower ratio had been used in most cases, and the higher in only a few extreme instances. As to the apparent discrepancy between the cost of the tunnels per lineal foot, as obtained by dividing the total cost of £6,000,000 by the 12½ miles of single-tunnel construction, which worked out at £91 per lineal foot, against £60 per lineal foot given as the cost for subaqueous iron-lined tunnels, the Author would state that the unit cost of £60 per lineal foot included engineering, management, plant, and general charges, but that the 12½ miles of single tunnel included all stations, switch and junction enlargements, and the like, and that the total cost of £6,000,000 included the cost of such stations, switch and junction enlargements, and in addition all shafts, foot-passages and stairways, chambers for ventilating and pumping-machinery, and in fact all underground structures accessory to the tunnels. It would thus be seen that the cost of these structures distributed over the total length of line accounted for the unit rate being about 50 per cent. higher than that given as the bare cost of the tunnel. As to the 500 feet of 19-foot tunnel that failed, some of these rings had machined joints, but most of them had unmachined joints filled with wooden packing. Owing to the records of the elevations of the old Pearson shield not being referred to a bench-mark on solid ground, no reliable facts could be deduced as to the amount of sinking, if any, during suspension of work. As a rule tunnels were built with the segments breaking joint. The standard type of air-lock for materials consisted of a cylinder, of ½-inch boiler-plate, 20 feet long and 6 feet in diameter, with the usual type of doors. The man-locks were oval in shape, 4 feet 1 inch by 3 feet 1 inch and 15 feet long. For sinking caissons various types of locks were used, some of which were patented and were leased from those controlling them. They all had various devices to permit the hoisting-cable to pass through the closed outside or top door. In what was perhaps the simplest and most successful kind, the top door consisted of a circular disk with the hoisting-cable passing through a stuffing-box, and remained always attached to the cable. The door was closed by clamps around the edge of the lock, and when the lock was open it was swung to one side with the material-bucket. In reply to Mr. Taylor, the steel apron for overhead protection while drilling rock had been attached to the old Pearson shield, while the removable protecting hood for the same purpose had been made so that it could be attached to any of the standard shields where necessary. In addition to the protection afford by these devices attached to the shields the soft-ground face

from the surface of the rock to the sliding platform or protecting hood was held in place with breast-boards strutted to the shield or through the doors. In regard to Dr. Zollinger's question why the tunnels had not been kept at the same depth from Caisson No. 2 right across the Hudson (Fig. 4, Plate 2), if the traffic from Hoboken terminal to Church Street terminal had been the only thing to be considered it would have been proper to build the tunnel at a deeper level; but as the tunnels under Washington Street were also to serve the traffic from Summit Avenue to the up-town tunnels, and it was desired to have the Erie station as near the surface as possible, the higher level was decided upon as being the more desirable. The Author.

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1 March, 1910.

WM. CAWTHORNE UNWIN, LL.D., F.R.S., Vice-President, in the Chair.

The Council reported that they had recently transferred to the class of

Members.

John Peachey Crouch.
Alfred John Hill.
Frank Mills.
Andrew Home Morton.
Edwin Bennett Brierley Newton.
Henry Sadler.
Charles Watson.

And had admitted as

Students.

Ernest Edwin Bailey, B.Sc. (Engineering) (*Lond.*)
Rupert Owen Beit.
George Lynton Howis Bradley.
John Stephen Burns.
Ernest Edward Dawson, B.A. (*Cantab.*)
Donald McKenzie Dinwiddie.
Charles Lambert Druitt.
Herbert Geoffrey Edleston.
Stuart Thomas Farrin.
Kenneth Byres Findlay.
Lewis Jex-Blake Forbes.
Arthur Trevor Gough, B.Sc. (*Birmingham.*)
Joseph Hawksley.
Henry Oliver Hill, B.A. (*Cantab.*)
Edwin Salter Hoare.
Frank Hudson.
Herbert Valentine Hughes.
Clifton Macnee Keiller.
Colin Hugh Macmillan.
Rawlyn Richard Maconchy Mallock, B.A. (*Cantab.*)
Leslie Martin Paterson.
Hubert George Salmond.
Alan Carrick Smith.
John William Abbott Steggall, B.Sc. (*St. Andrews*).
Herbert Lloyd Tate.
Stanley Edward Weston Taylor.
Arthur Temple Thorne.
Eric Hinton Griffith Tomblings.
Arthur Percy Williams.

The Scrutineers reported that the following Candidates had been duly elected as

Members.

ALFRED SHARMAN GILES.
HENRY JONES.
JAMES FOSTER KING.
FREDERICK AUGUSTUS CORTEZ-LEIGH.
HENRY PERCY MAYBURY.
HUGH HENRY GORDON MITCHELL.
SMELTER JOSEPH YOUNG.

Associate Members.

ERNEST RICHARD BRANSTON.
THEOBALD STUART BUTLER, Stud. Inst. C.E.
THOMAS CLARK, B.Sc. (Engineering) (*Lond.*)
ERIC DAVIES, B.Sc. (*Glas.*)
WILLIAM DALKEITH DONKIN, B.E. (*Sydney*).
JOHN ELLIS, Stud. Inst. C.E.
WILLIAM MUIR HAYMAN.
NORMAN BELL HOY, Stud. Inst. C.E.
WILLIAM PERCY JOHNSON.
MALCOLM GLEN KIDSTON, B.Sc. (*Glas.*)
REGINALD FAIRFAX MIDDLETON, Stud. Inst. C.E.
PERCIVAL MORTON NORRIS.
REGINALD PETERS, Stud. Inst. C.E.
BERNARD PRICE.
HUBERT RAINE, Stud. Inst. C.E.
MERVYN FREDERICK RYAN.
JOHN EDWARD SEARS, Jun., B.A. (*Cantab.*)
EGBERT GORDON WOODWARD, Stud. Inst. C.E.

The discussion on Mr. C. M. Jacobs's Paper, "The Hudson River Tunnels of the Hudson and Manhattan Railroad Company" occupied the evening.

LONDON: PRINTED BY WILLIAM CLOWES AND SONS, LIMITED,
DUKE STREET, STAMFORD STREET, S.E., AND GREAT WINDMILL STREET, W.

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